Large cryogenic detectors

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EXCELENCIA MARÍA DE MAEZTU

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Berkeley Lab

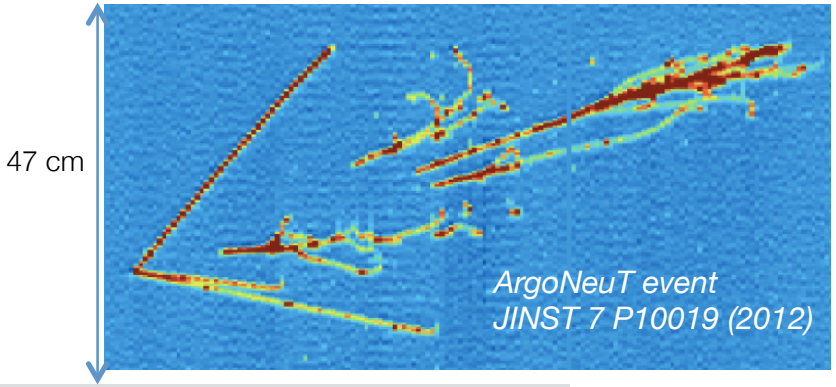
Outline

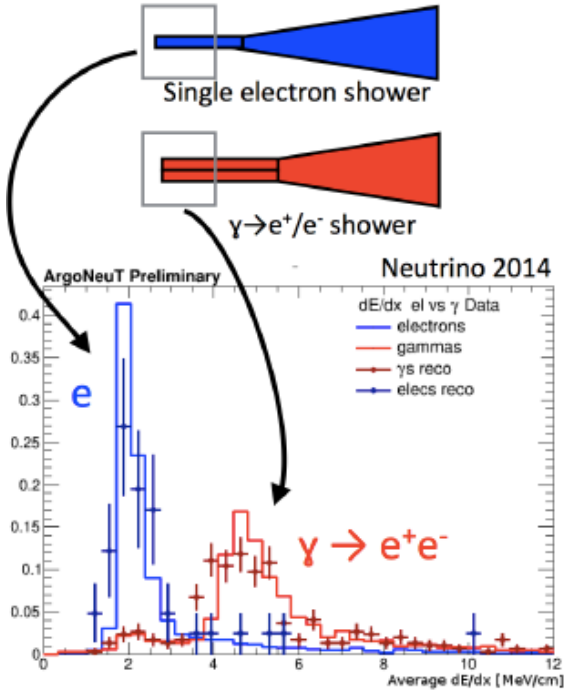
- Large cryogenic TPC detector challenges
- ICARUS detector performance
- Short-baseline Neutrino Program at Fermilab
  - SBND, MicroBooNE & (new) ICARUS
- The LBL Neutrino Program at FNAL: the LBNF/DUNE project
  - Single-phase LAr TPC detector
  - Dual-phase LAr TPC detector
- ProtoDUNEs at the CERN Neutrino Platform
- Conclusions

Large cryogenic TPC challenges

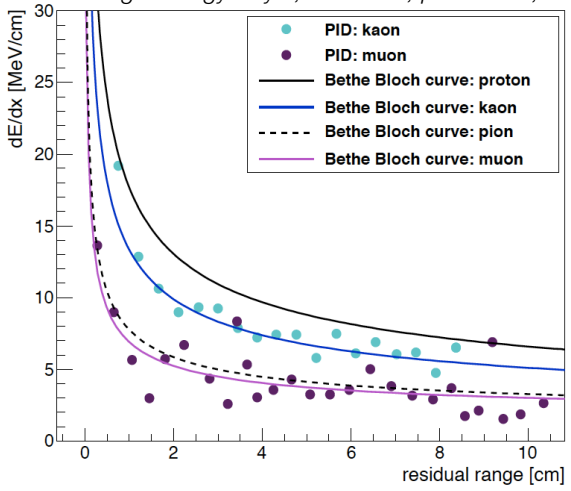
Liquid Argon technology

- **LAr TPC is the leading technology** for future short/long-baseline accelerator **neutrino oscillation experiments**
- The LAr TPC technology provides:
  - **excellent 3D imaging** capabilities
    - few mm scale over large volume detector
  - **excellent energy measurement** capability
    - totally active calorimeter
  - **particle ID** by dE/dx, range, event topology, …
  - **scalability** to large detectors
    - high signal efficiency and background discrimination





Adv. High Energy Phys., vol. 2013, p. 260820, 2013



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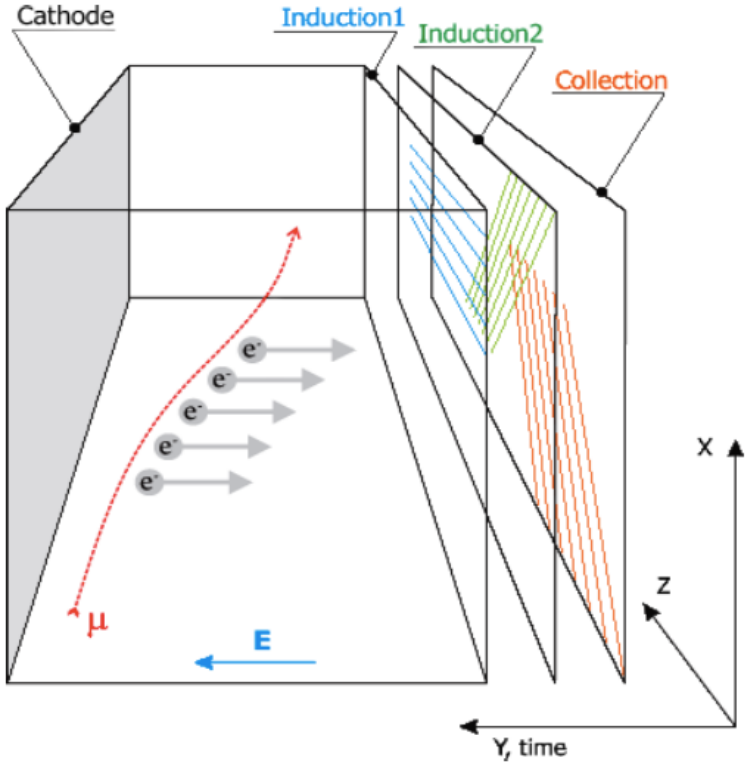
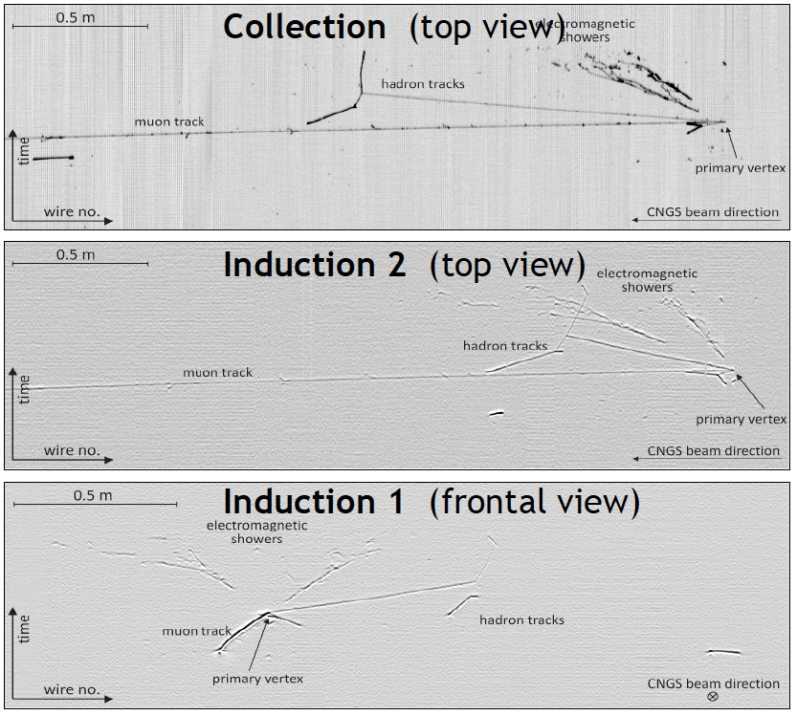
LAr TPC detection principle

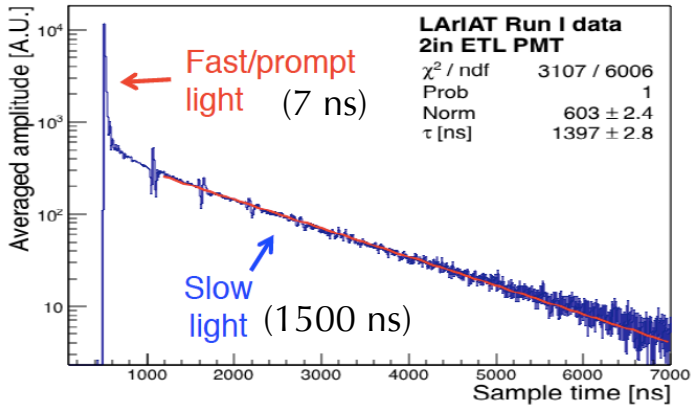




- Charged particles ionize Ar; electrons drift to anode wires (~ms) and scintillation light gives the drift time
- 3D spatial reconstruction from wire planes
- **Charge** measurement by collection plane
- Absolute time from scintillation **light** signals

Light: ~40000 γ/MeV at E=0

Average waveform of through-going muons



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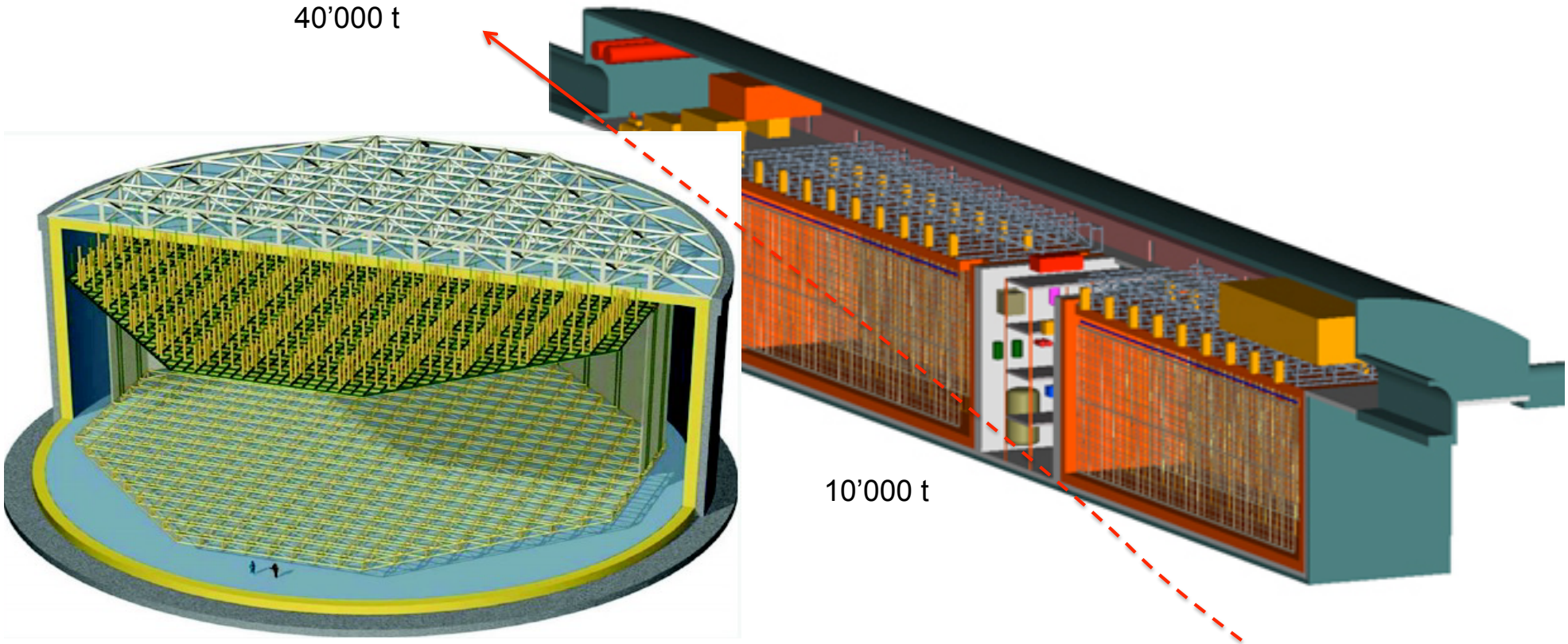
Large (~kton) LAr TPC challenges

1. **Large cryogenic vessels**
   - Very large LAr masses are needed
2. **Liquid purification**
   - Needed to ensure long drift path of ionization electrons without attenuation
3. **High voltage systems**
   - 0.5-1 kV/cm drift field
4. **Electronics and DAQ**
   - Low noise electronics
5. **Scintillation light detection**
   - Long term performance

LAr experimental path



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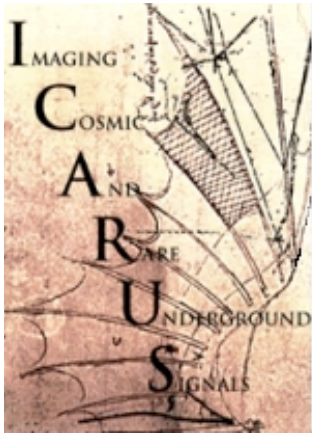
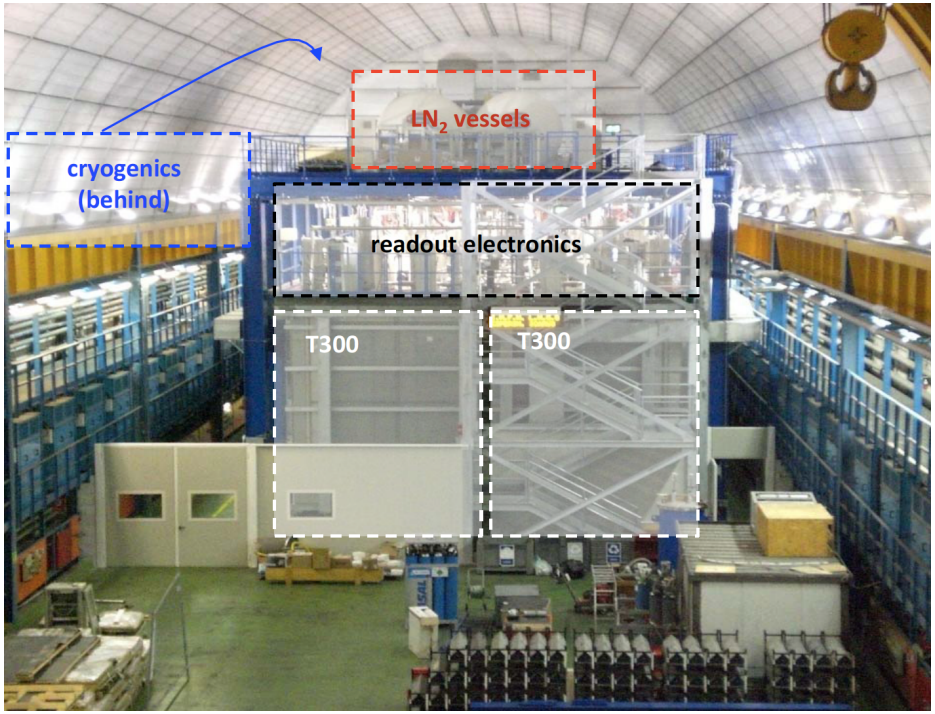
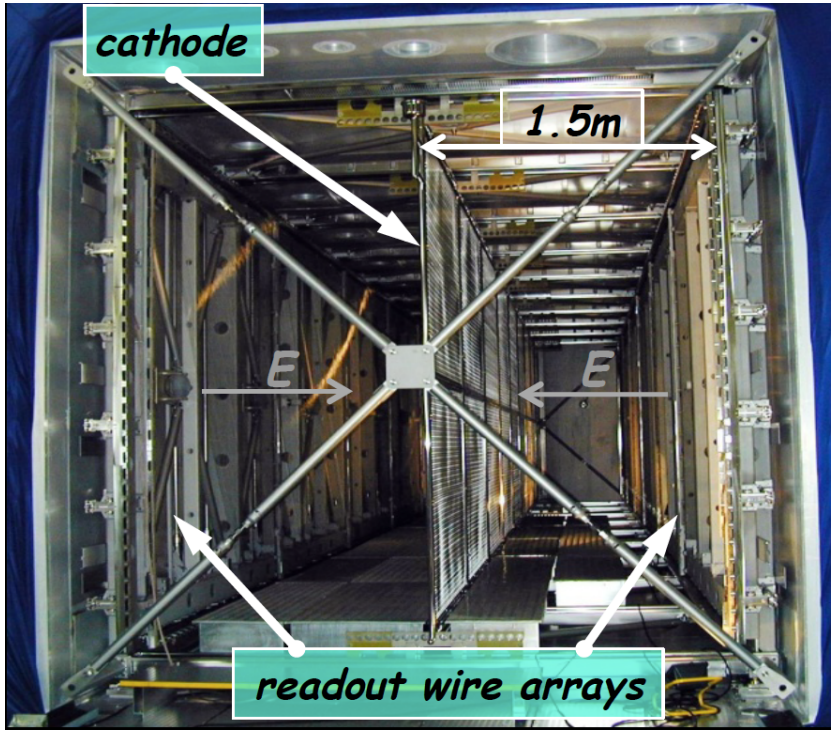


ICARUS at LNGS

The T600 ICARUS detector

ICARUS @LNGS Hall B





- 2 identical modules (T300)
- 3.6 x 3.9 x 19.6 m^3 each
- LAr active mass: 476 ton
- Drift length = 1.5 m (1 ms)
- HV = -75 kV; E = 0.5 kV/cm

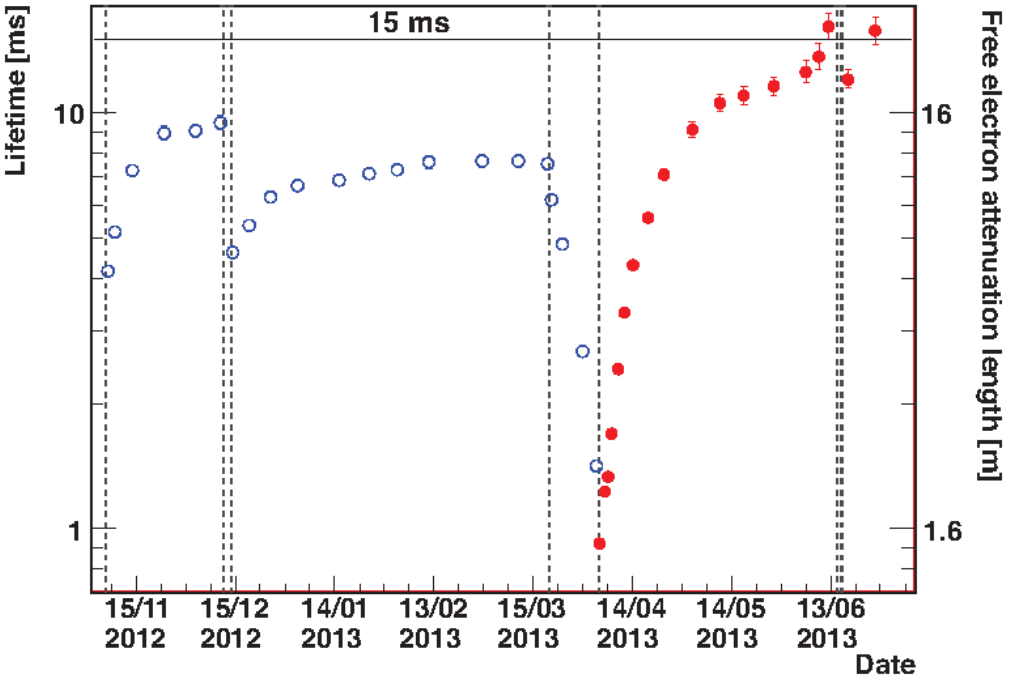
- 4 wire chambers
- 2 chambers per module
- Three non-destructive readout wire planes per chamber (at 0, ±60º)
- 54000 wires, 3 mm pitch and plane spacing
- 74 8″ PMTs for light detection

ICARUS performance

- ICARUS T600 detector is the largest operational LAr TPC built so far
- A single T300 module was tested at surface in Pavia in 2001
- ICARUS was deployed and operated from 2010 to 2013 at the underground LNGS exposed to the CNGS beam (8.6 x 10^{19} POT) and cosmic rays
- ICARUS has demonstrated **excellent detection properties**:
  - precise *3D topology* and high spatial resolution and accurate ionization measurement
  - *good calorimetric energy reconstruction* ($\sigma(E)/E = 11\%/\sqrt{E}$ (MeV) + 2% for low-E e^-, $\sigma(E)/E = 3\%/\sqrt{E}$ (GeV) for e.m. showers, $\sigma(E)/E = 30\%/\sqrt{E}$ (GeV) for hadronic showers)
  - *good particle identification* via dE/dx and e/γ separation
  - *momentum reconstruction* of non-contained μ via multiple scattering ($\Delta p/p$ ~16% in the 0.4-4 GeV range)
- ICARUS is now part of the SBN program at FNAL as one of the 3 detectors at different baselines to look for sterile neutrinos by 2018

ICARUS detector demonstration

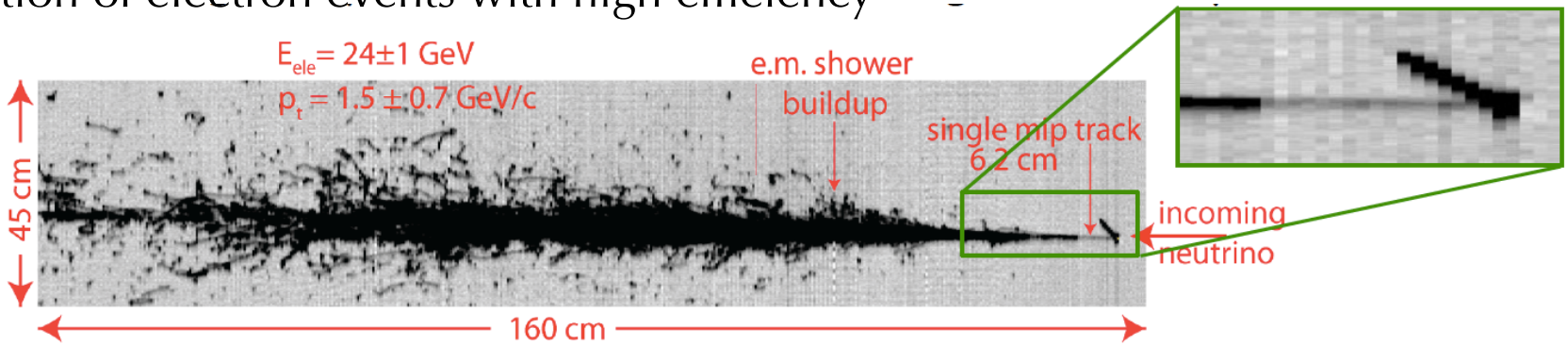
- **Very long electron mobility:**
  - New industrial purification methods have been developed to continuously filter and recirculate both in liquid (100 m^3/day) and gas (2.5 m^3 /hour) phases
  - $\tau_e > 7$ ms measured during ICARUS run at LNGS
  - $\tau_e > 16$ ms (< 20 ppt O_2 equiv.) with new pump installed



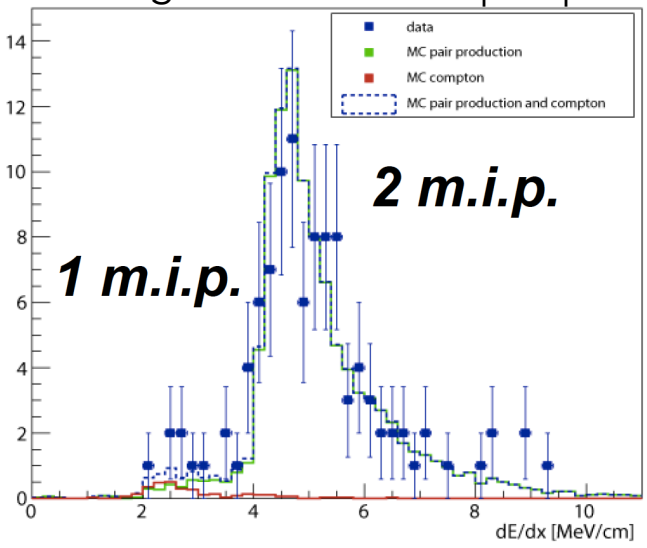
FUNDAMENTAL STEP PAVING THE WAY TO HUGE DETECTORS

ν_e identification in ICARUS

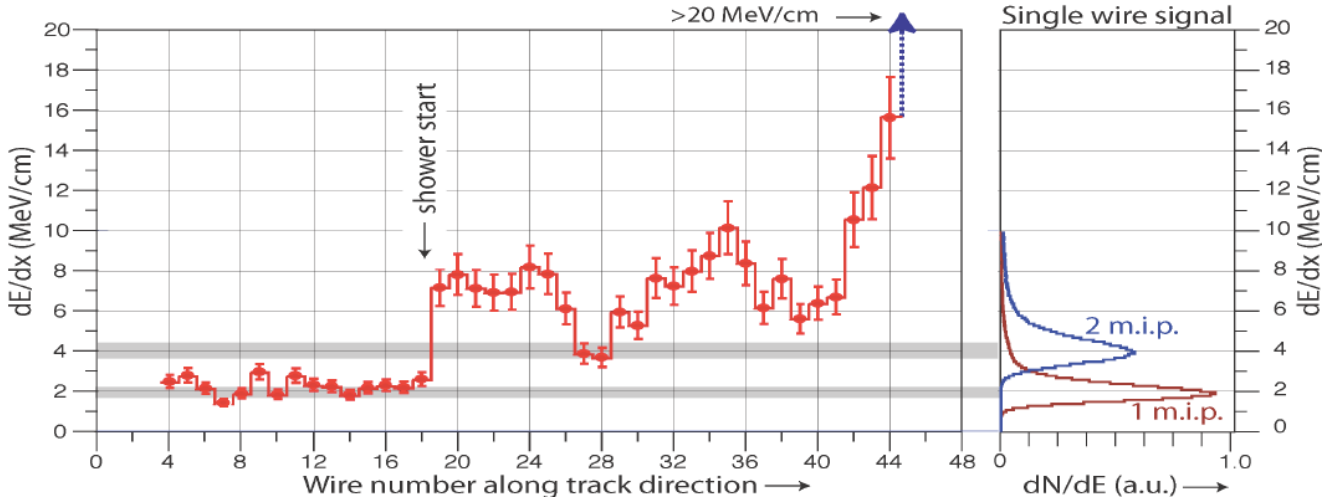
- Unique feature of LAr to **distinguish electrons from gammas** reducing important background events
- Identification of electron events with high efficiency



Data from e.m. shower (π^0 decays)
MC single electrons and pair production



Evolution of dE/dx from a single track to an e.m. shower



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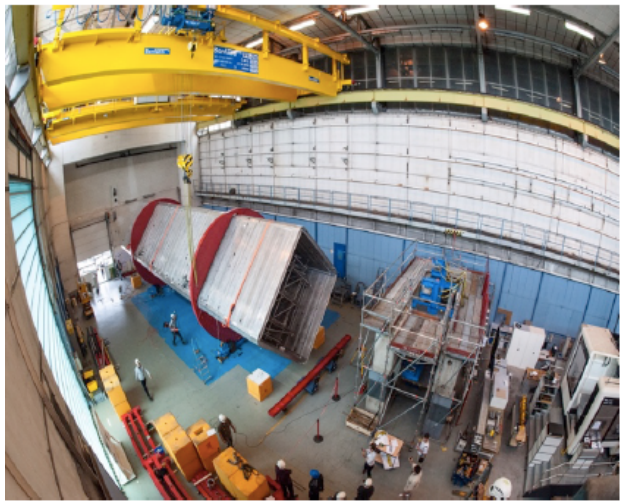
ICARUS status

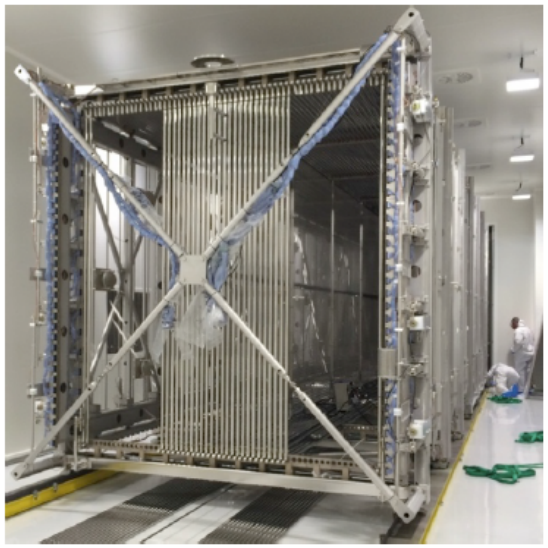
- INFN/CERN/US WA104 program: ICARUS has been moved to CERN late 2014 for overhauling to operate at surface
- ICARUS will be delivered to Fermilab (~April 2017) and operated at the short-baseline neutrino beam by end 2018
- Detector **overhauling**:
  - New generation of cold cryostats and new purely passive insulation
  - Refurbishing of the cryogenic and purification systems
  - New cathode with better planarity
  - Upgrade of the light detection system: 360 PMTs behind the wire planes
  - New faster, higher-performance readout electronics
- A muon tagging system is designed and constructed in parallel

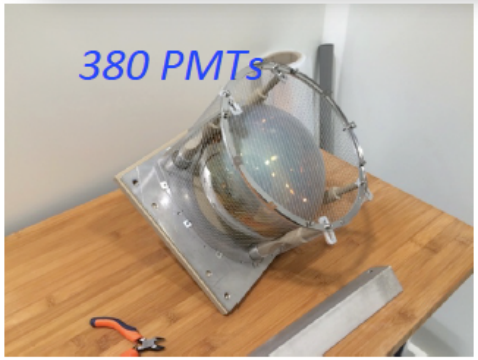
ICARUS at CERN

New aluminum cold vessel being assembled at CERN

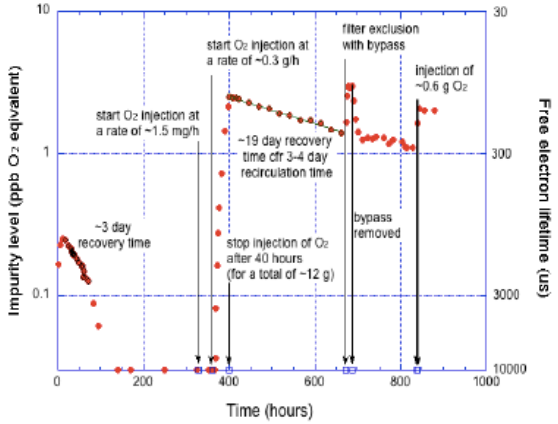


TPC cabling / "cold" biasing circuitry

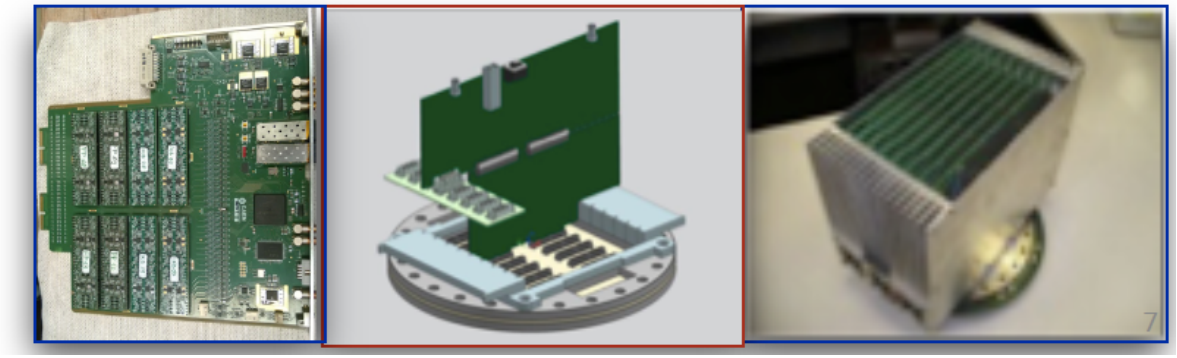




New purification system efficiency study



New readout board, feed through flange and compact crate



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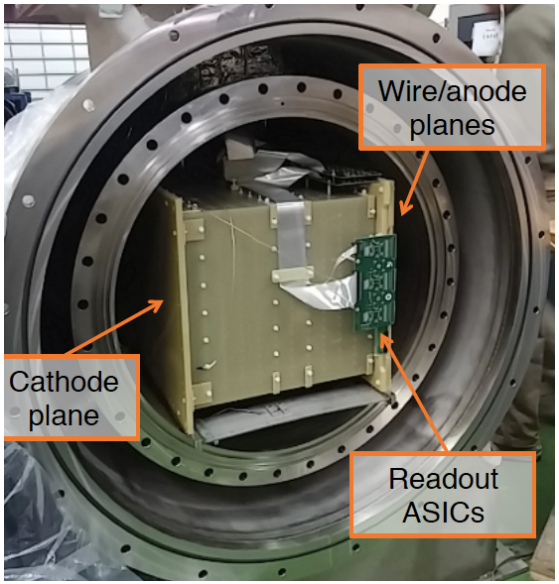
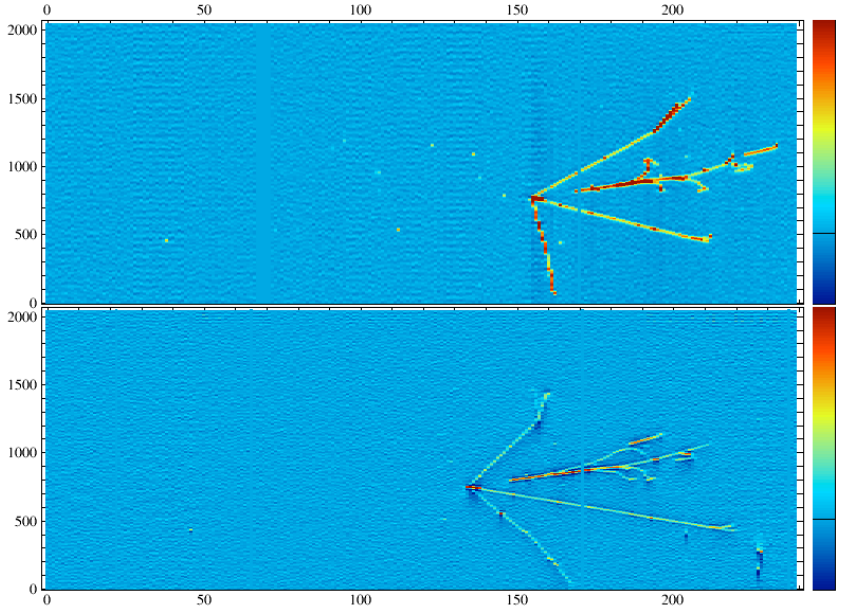
Fermilab

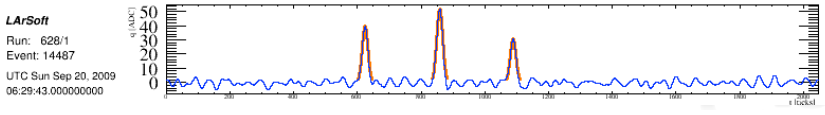
The SBN Program at FNAL

ArgoNeuT @NuMI (➜ LArIAT)

- 90 cm long x 40 cm tall x 47 cm drift
  - Active volume: 175 litres
  - 2 wire planes: induction and collection (4 mm wires spacing)
  - No light detection system
- Took **data from 09/2009 to 02/2010 at the NuMI beam**
  - 2 weeks in neutrino mode & 4 months in antineutrino mode
  - 0.1 - 20 GeV energy of neutrino beam
- Goals:
  - Measure ν-Ar cross-sections
  - Calibration of LAr detectors
  - Study nuclear effects
  - Reconstruction techniques
- **Main results**:
  - Muon neutrino and antineutrino cross sections
  - Crossing muon analysis
  - Charge recombination
  - Back to back protons
  - Coherent pion production

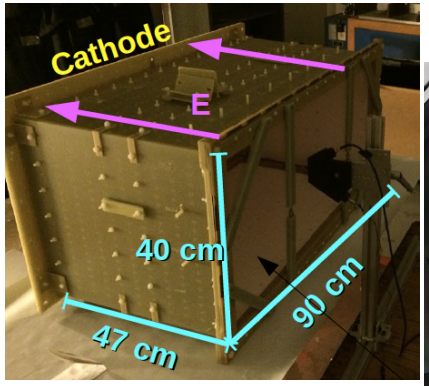


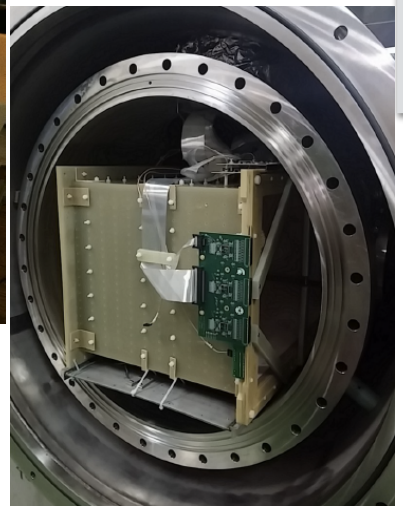


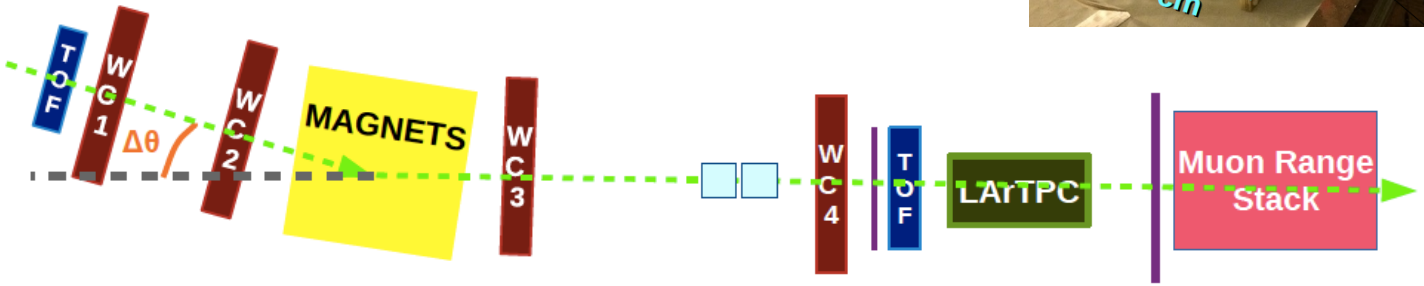


LArIAT

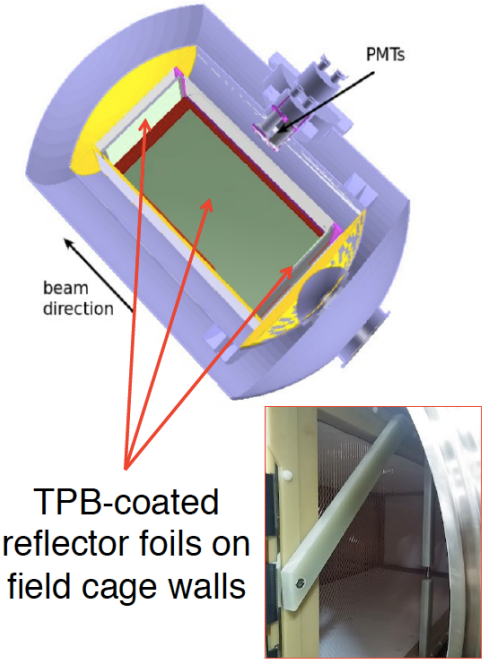
- Uses the refurbished ArgoNeuT TPC
- Data in **May 2015**: 3 + 5.5 months
- 170 litres LAr, 500 V/cm drift field
- 2 wire planes (±60º orientation, 4 mm pitch)

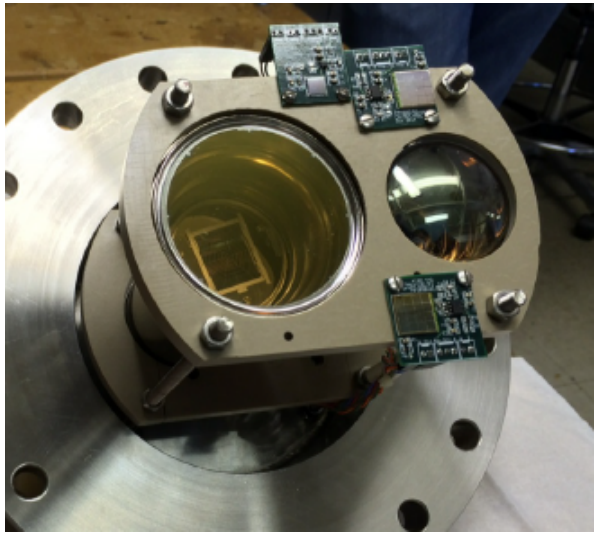






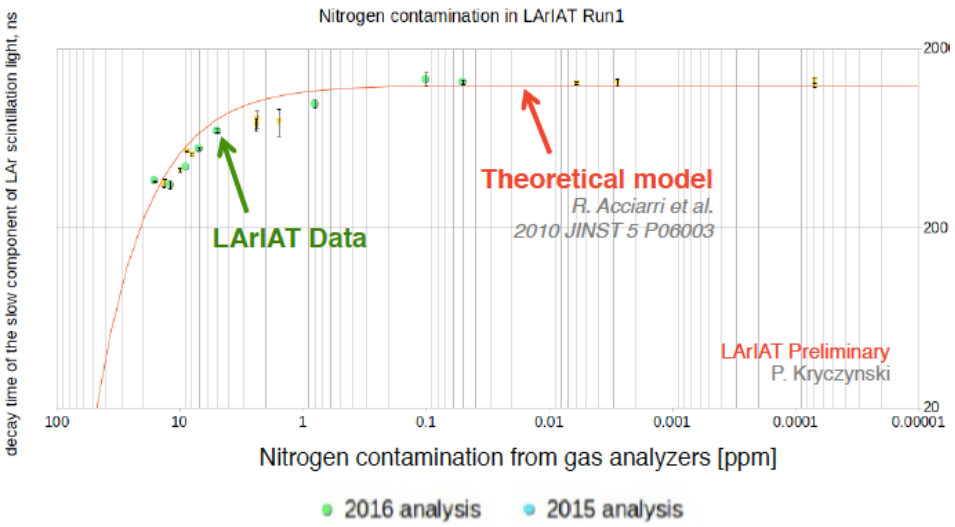
- Light system:
  - 1 3″ + 1 2″ cryo PMTs
  - 3 SiPMs
- TPB-coated reflectors to increase the light detection and the uniformity (2.4 pe/MeV in a 2″ PMT)

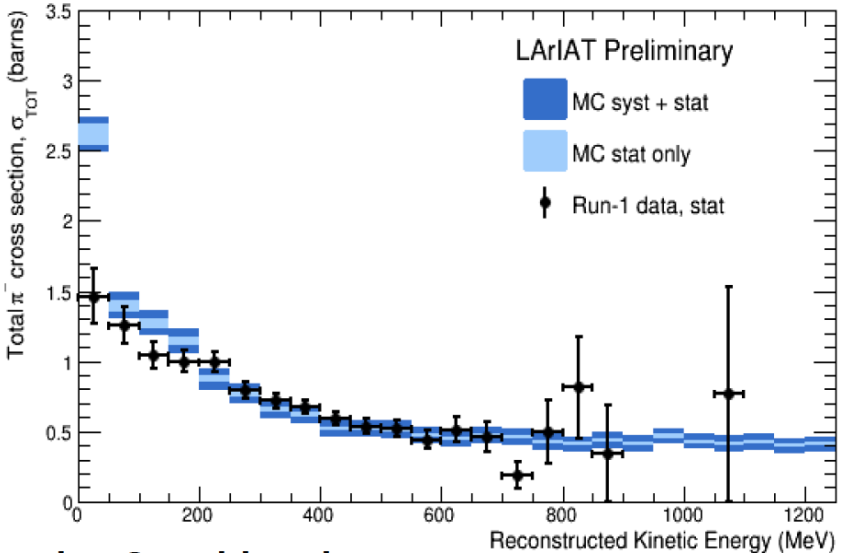


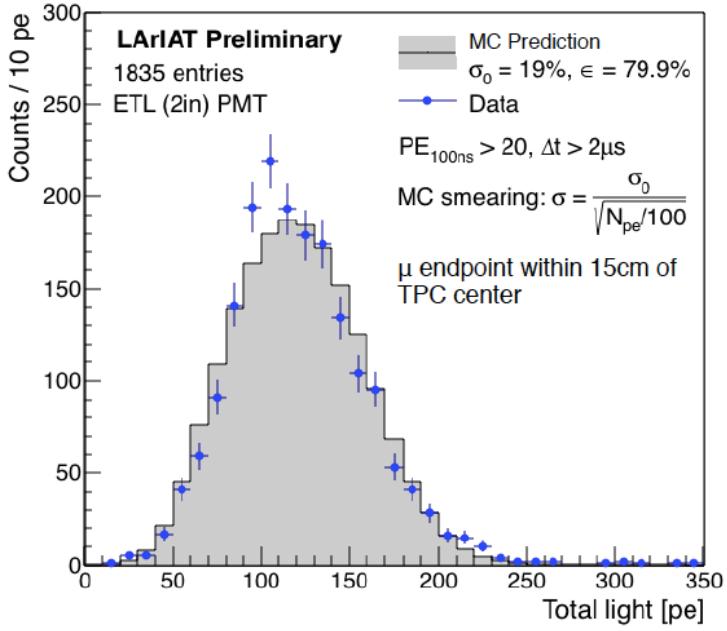


LArIAT ongoing analysis

- N_2 contaminations
- Calorimetry enhancement
  - Combine charge and light to improve linearity between energy deposited and charge collected
- Cosmic muon Michel electron studies
- π^--Ar cross section measurement







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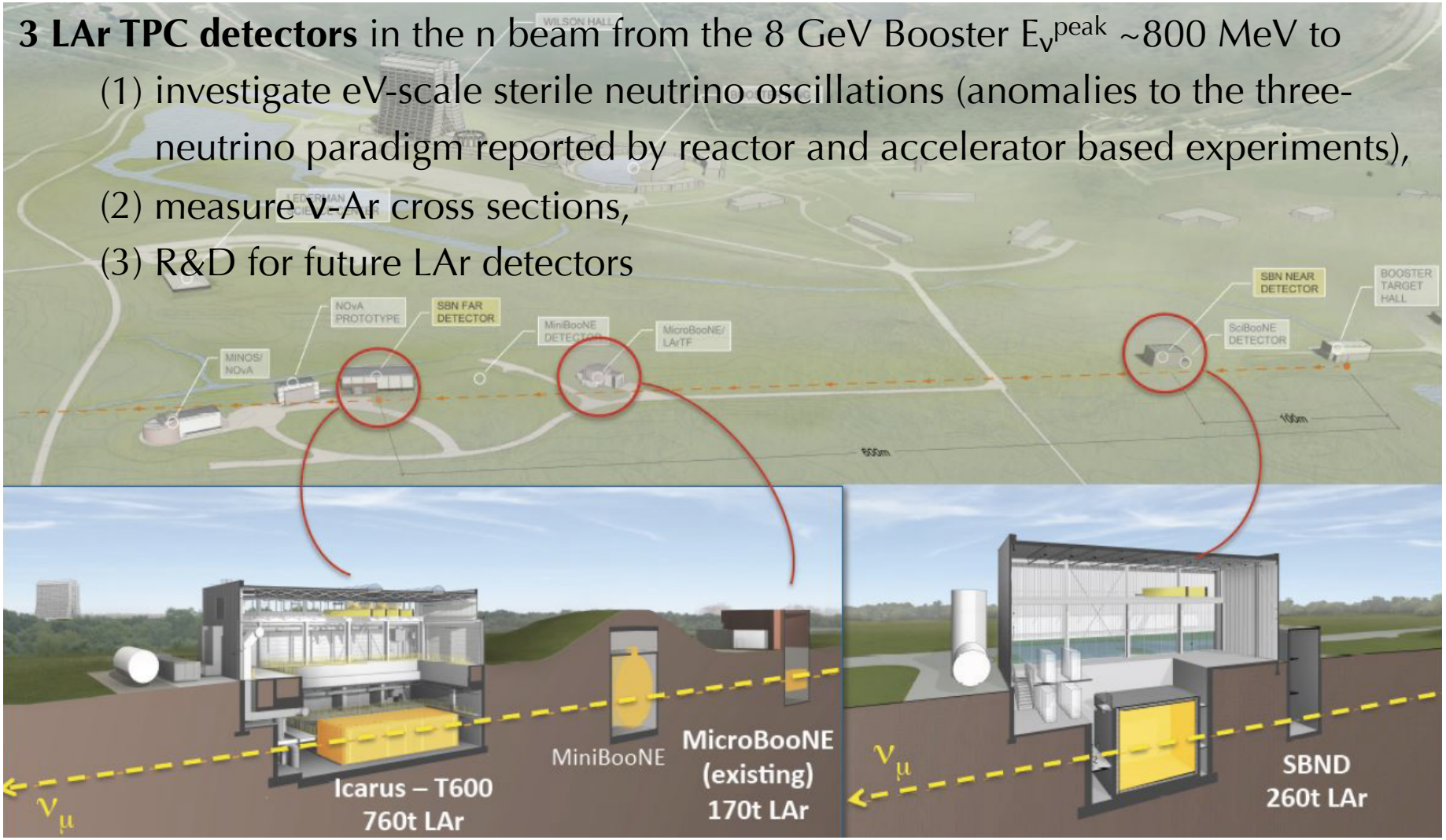
SBN: A multi-LAr TPC program

3 LAr TPC detectors in the n beam from the 8 GeV Booster E_ν^{peak} ~800 MeV to

(1) investigate eV-scale sterile neutrino oscillations (anomalies to the three-neutrino paradigm reported by reactor and accelerator based experiments),

(2) measure ν-Ar cross sections,

(3) R&D for future LAr detectors



600 m 470 m 110 m

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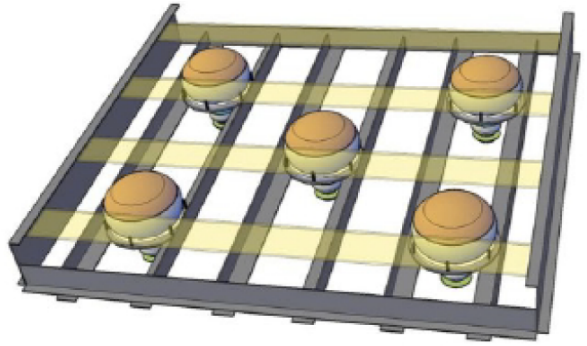
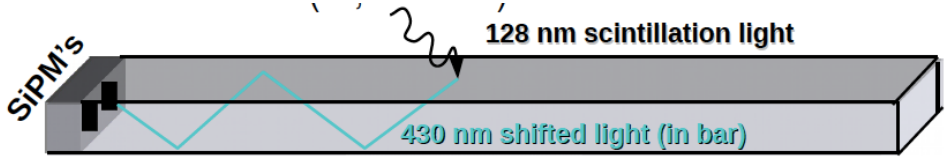
Detector parameters

Detector Component	SBND	MicroBooNE	ICARUS@SBN
TPC Active Volume	4 × 4 × 5 m	2.5 × 2.3 × 10.4 m	3.6 × 3.9 × 19.6 m
TPC Active Mass	112	89	476
TPC Drift Time (at 500V/cm E-field)	1.28 ms	1.6 ms	0.95 ms
TPC Wire Orientation	0° (collection), ±60° (induction)		
Wire/plane spacing	3mm	3mm	3mm
Number of wires	11264	8192	53248
Nominal Drift HV	100 kV	128 kV	75 kV
Analog readout electronics	cold CMOS	cold CMOS	warm
Digital readout electronics	ADC cold, FPGA cold	warm	warm
Light collection	120 8" PMTs & scint. bars	32 8" PMTs	360 8" PMTs

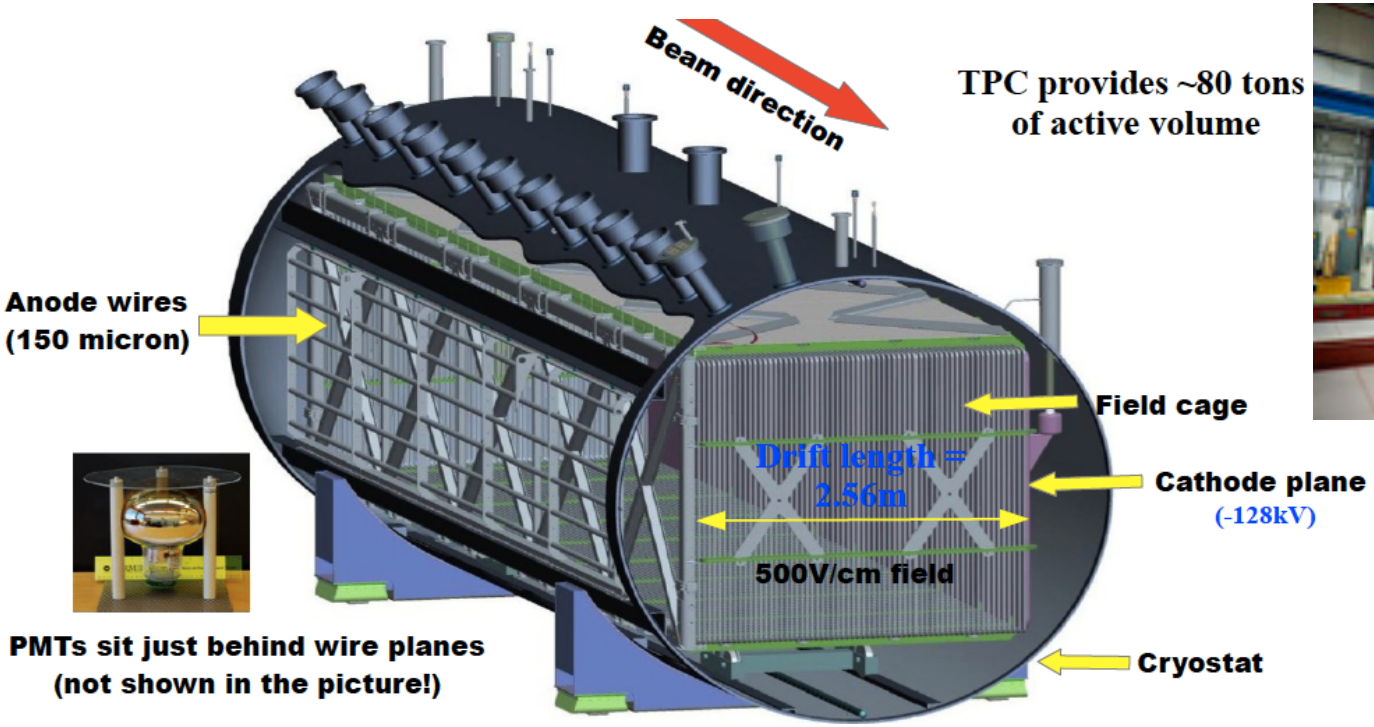
- **Synergies with DUNE**:
  - Modular TPC design with large anode plane assemblies
  - Test scintillator bar photon detector design
  - Cold electronics readout chain





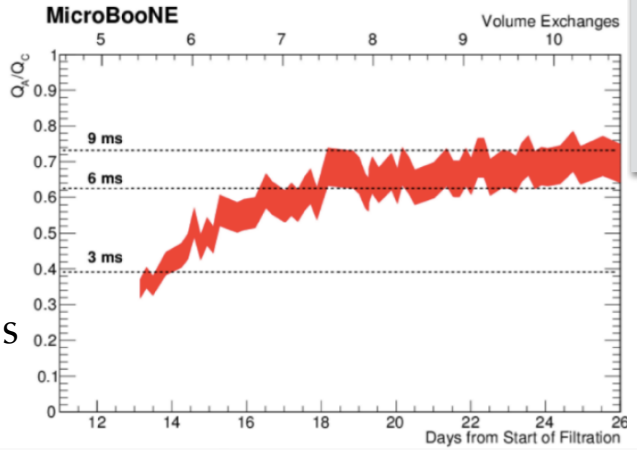
MicroBooNE @BNB

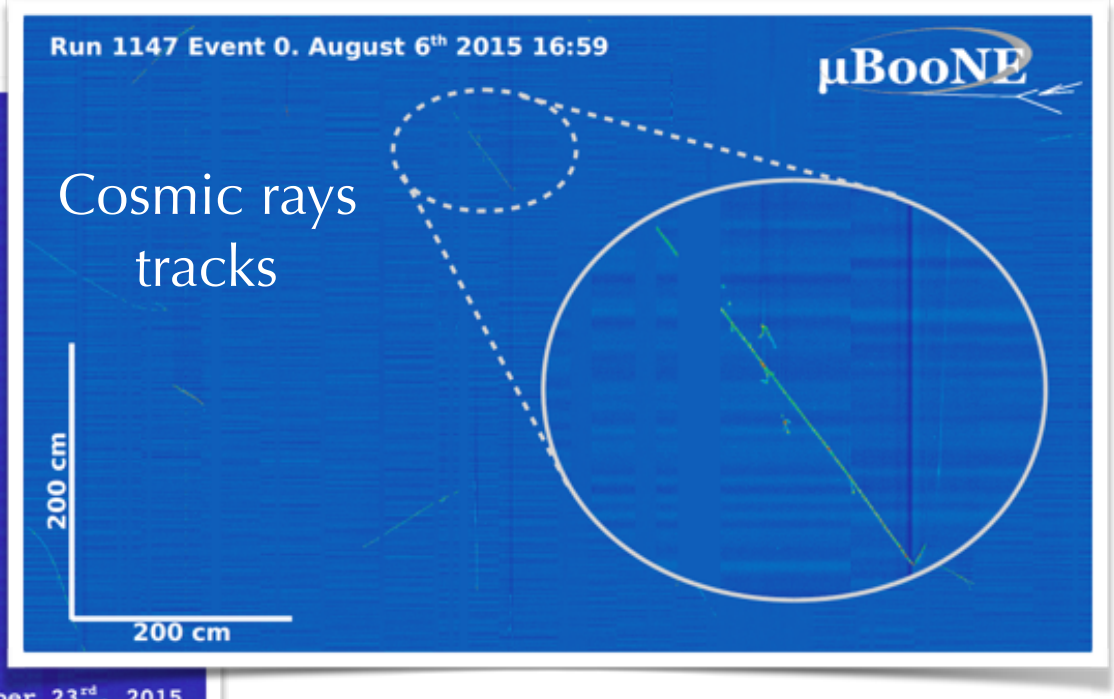
- 170 ton (89 ton active) LAr TPC neutrino experiment in the Fermilab Booster Neutrino Beam line (at 470 m from start of the BNB)
  - 10.3 m long x 2.3 m tall x 2.5 m drift, 3 mm wire pitch, -128 kV cathode voltage
  - 32 8″ cryogenic PMTs behind the anode wires
- Physics **goals**:
  - Address the low-energy electron-like excess observed by MiniBooNE
  - Make high statistics measurements of ~1 GeV neutrino interactions in Ar and study nuclear effects



MicroBooNE status

- Assembly and installation complete
- Detector filled with ultra pure LAr
- First neutrino beam from the Fermilab Booster accelerator on **Oct 15, 2015** (3.4 x 10^{20} POT taken)
- Stable running with drift HV of 70 kV with e- lifetime of > 6 ms
- Hardware fixes in Oct'16 improved noise level





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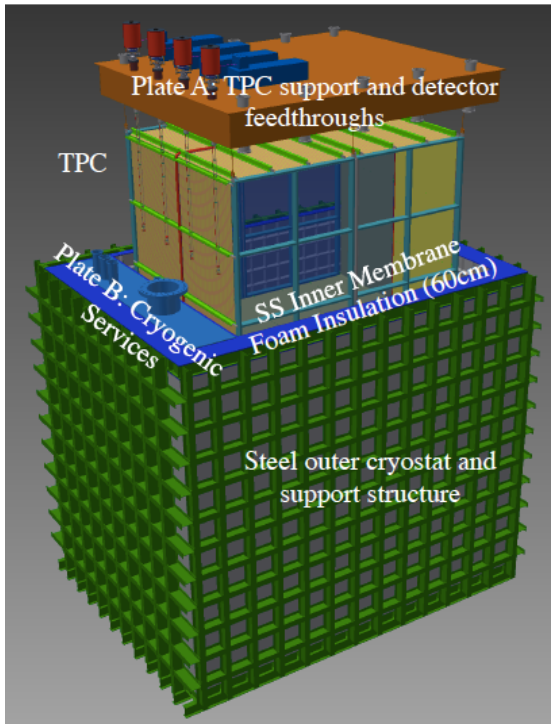
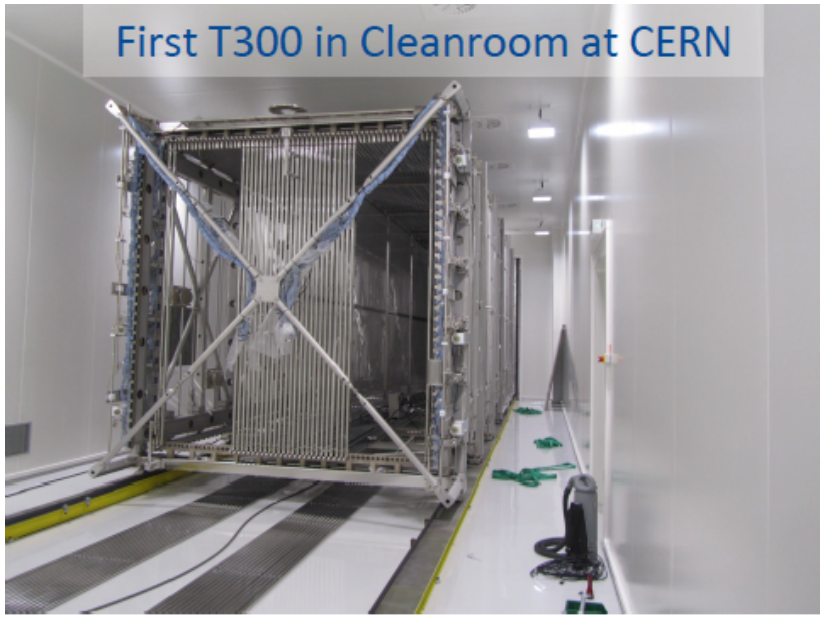
SBND & ICARUS at SBN program

- Another two LAr detectors being constructed and operated soon

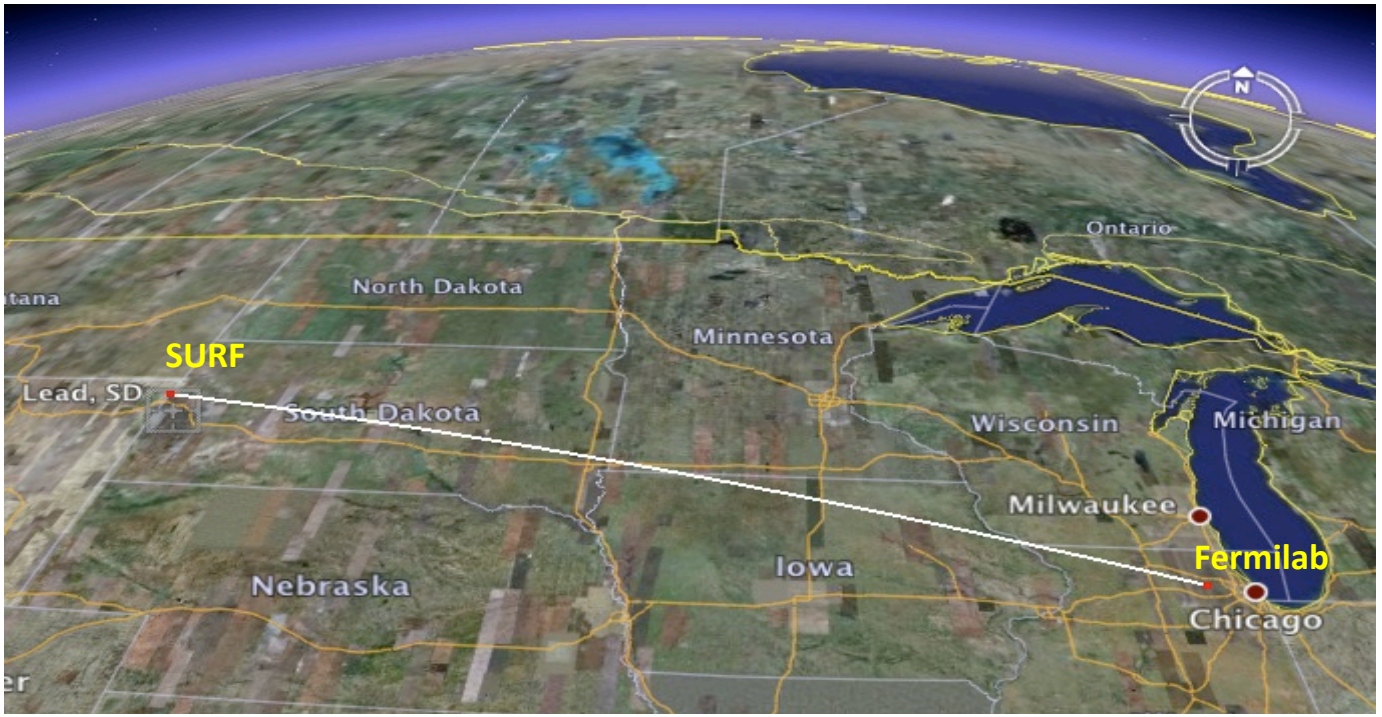
- **SBND**: under design phase
  - 112 ton active volume (4 x 4 x 5 m^3)
  - To be located 110 m from the BNB neutrino source
  - To be operational end of 2018
  - Large data sample for neutrino-argon interaction studies in the GeV energy range

- **ICARUS**: under refurbishment at CERN
  - Was the first large scale LAr TPC to run in a neutrino beam line (CNGS from 2010 to 2013)
  - Will be shipped to Fermilab in 2017

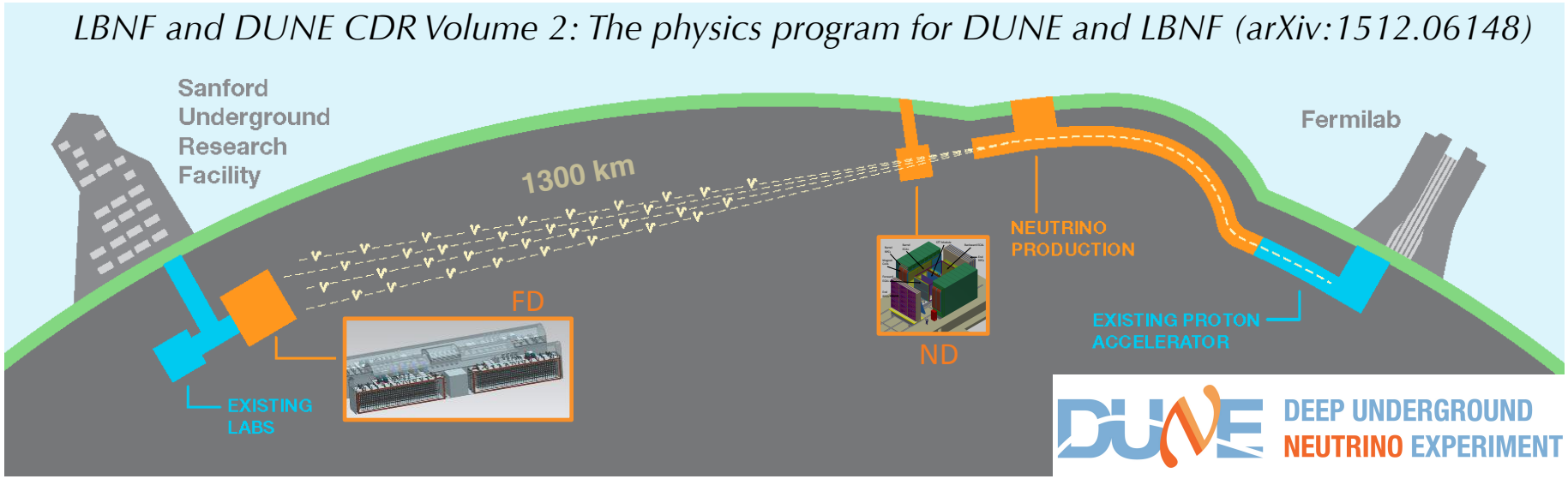




LBNF/DUNE at FNAL

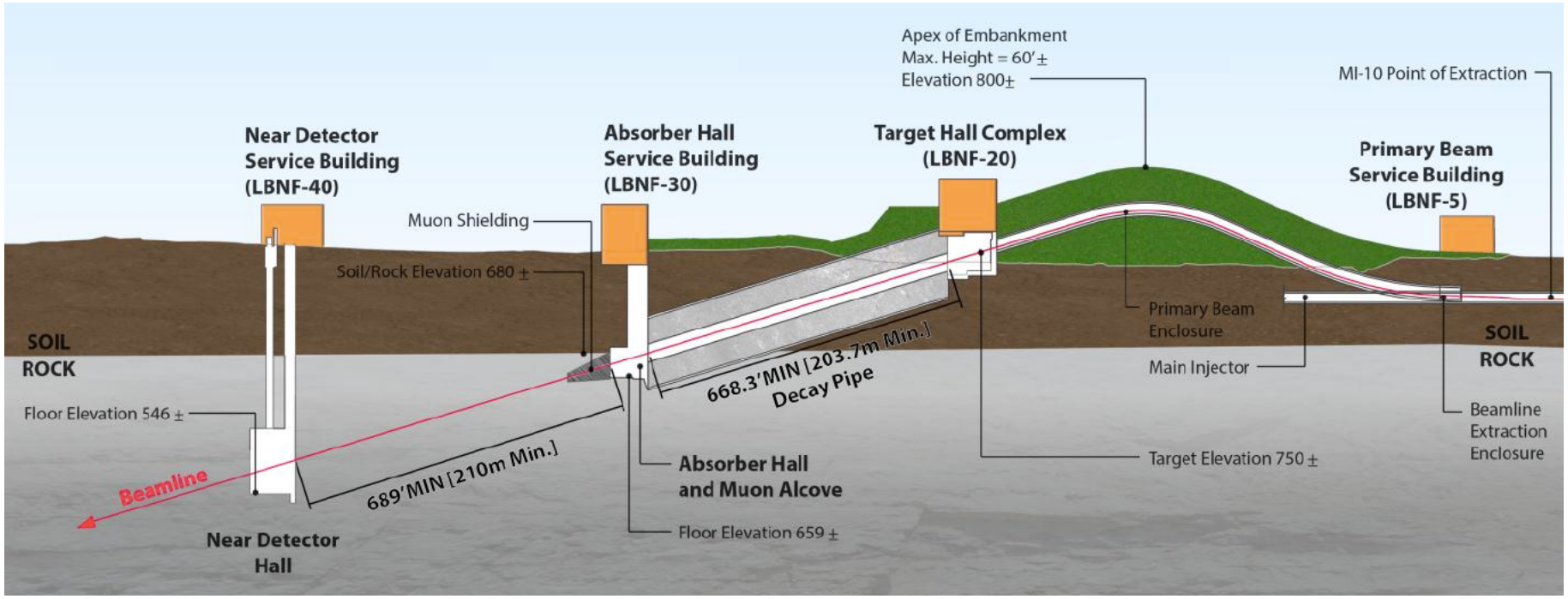


The LBNF/DUNE Project

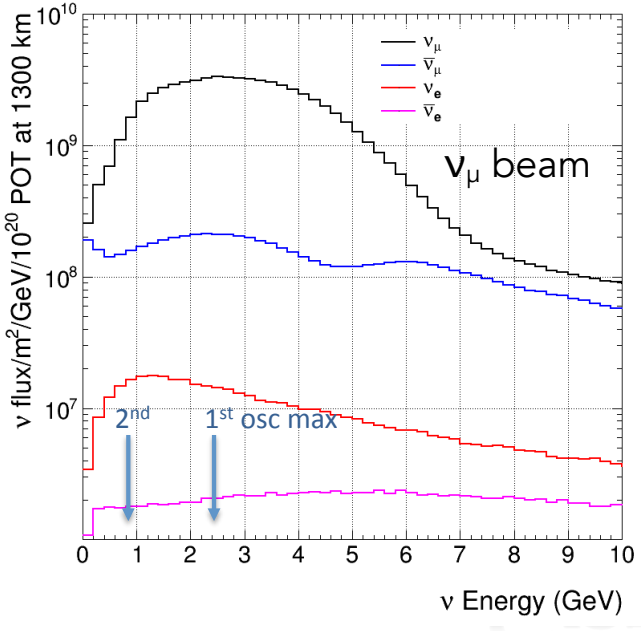


- **D**eep **U**nderground **N**eutrino **E**xperiment: **40 kton LAr TPC** far detector **at 1480 m depth** (4300 mwe) at SURF measuring neutrino spectra **at 1300 km** in a wide-band high purity ν_μ beam with peak flux at 2.5 GeV operating at ~1.2 MW and upgradeable to 2.4 MW
- **4 x 10 kton** (fiducial) modules (**single and/or dual-phase**) with ability to detect LBL oscillations, SN burst neutrinos, nucleon decay, atmospheric vs

LBNF project at FNAL

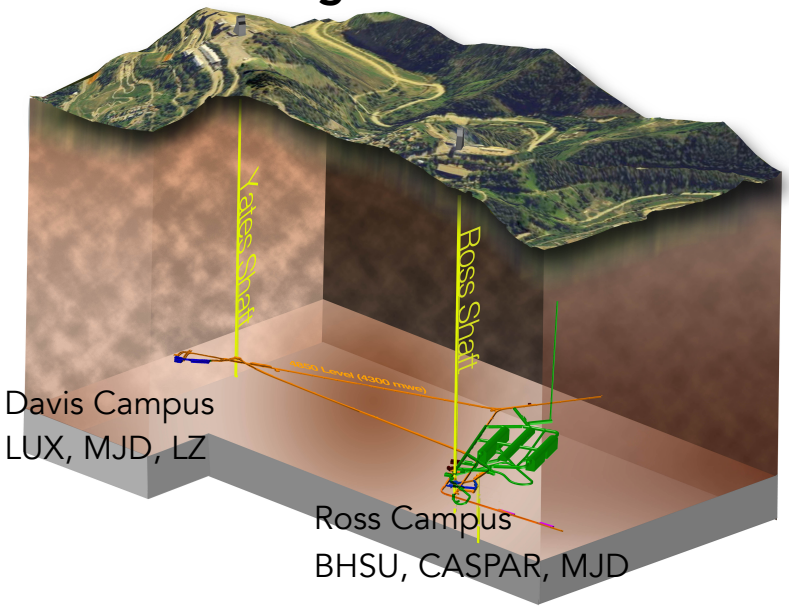


- Primary 60-120 GeV proton beam from FNAL main injector
- Wide energy spectrum covers the 1st and 2nd oscillation maxima
- Near Detector Hall at 574 m
- Initially 1.2 MW, upgradable to 2.4 MW

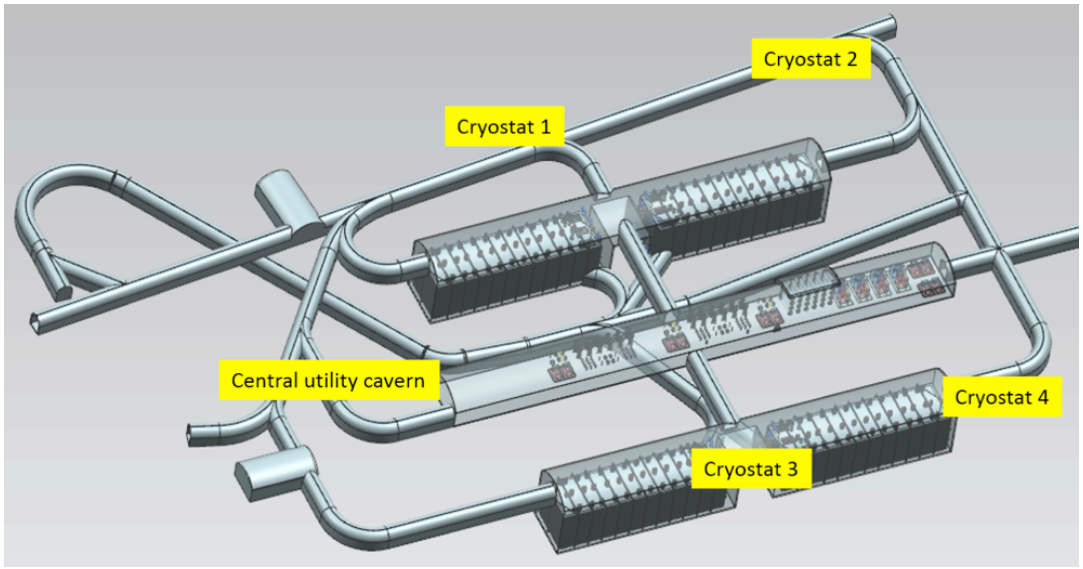


Staged approach to 40 kton

Sanford Underground Research Facility

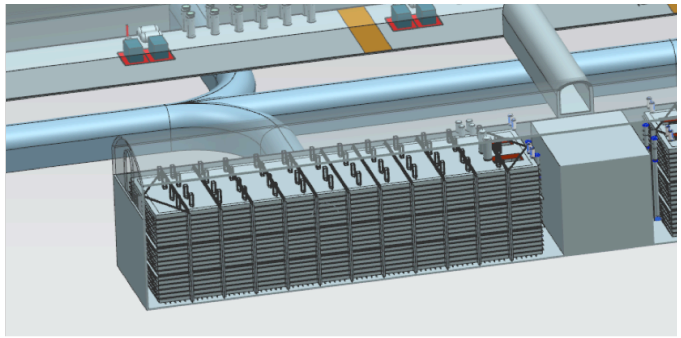


DUNE Far Detector at SURF

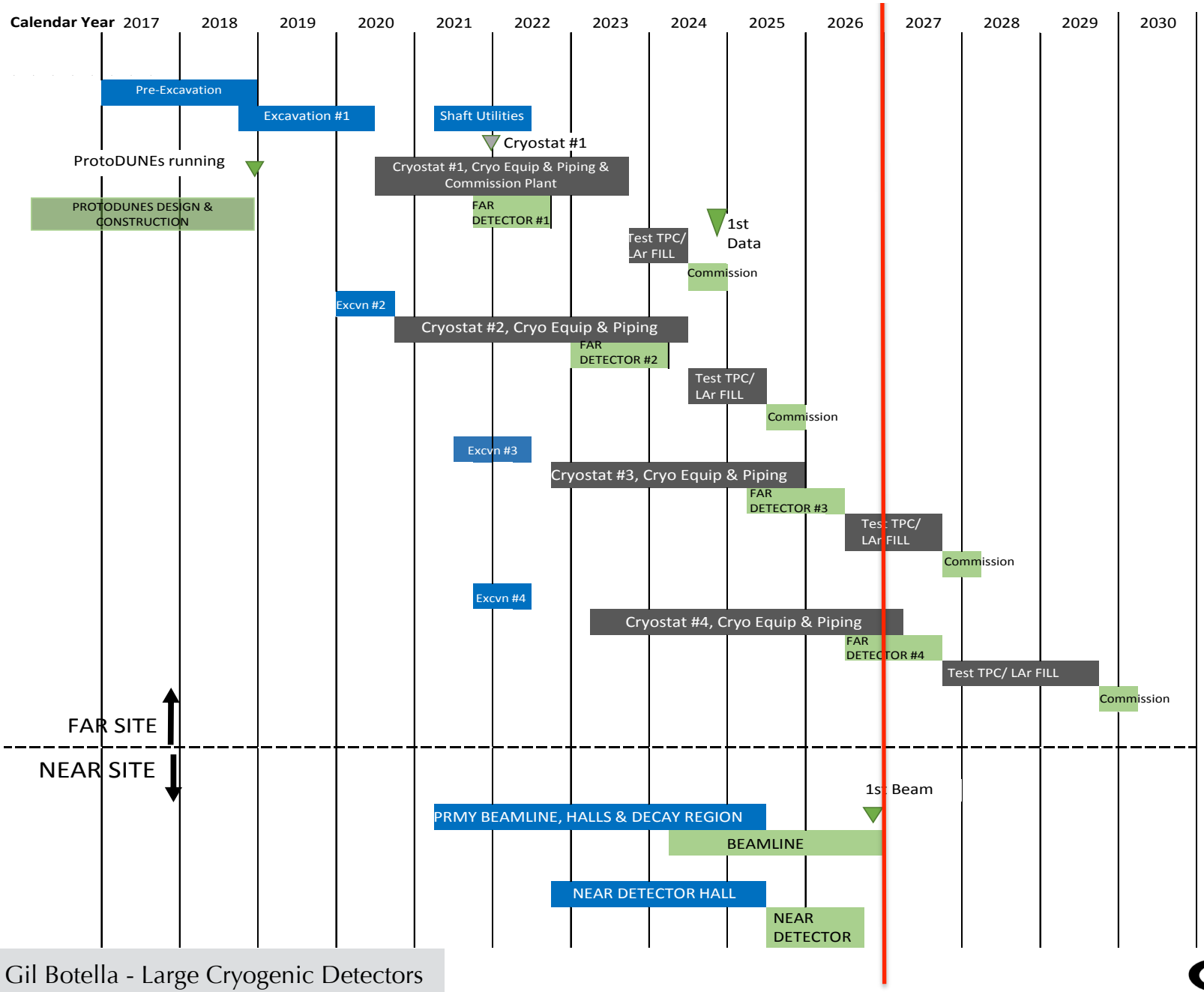


LBNF and DUNE CDR Volume 4: The DUNE Detectors at LBNF (arXiv:1601.02984)

- Four caverns hosting **four independent 10 kton (fiducial mass) FD modules**
  - Assumed four identical cryostats 15.1 (W) x 14.0 (H) x 62 (L) m^3
  - Phase-in approach
  - Allows alternate designs (single vs dual-phase LAr TPCs)
- Installation of #1 module starts in 2022
- Complete TDR should be ready for 2019



LBNF/DUNE construction schedule



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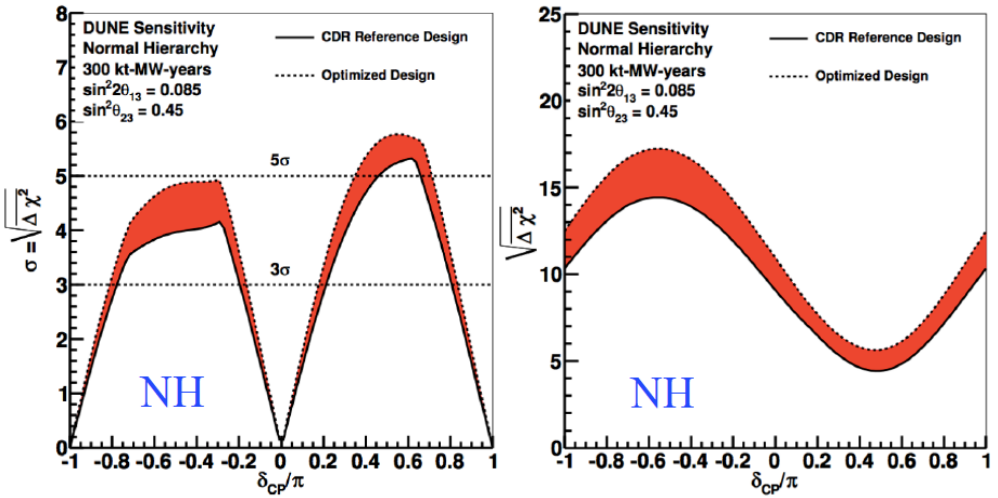
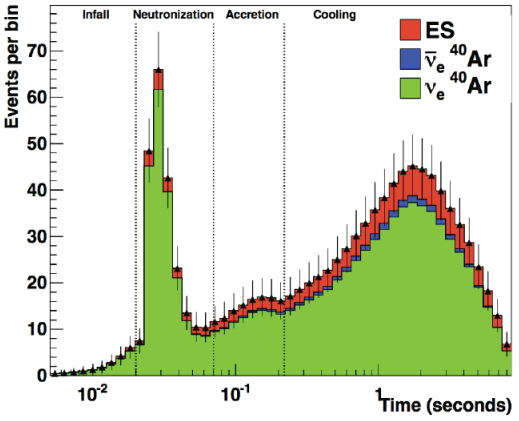
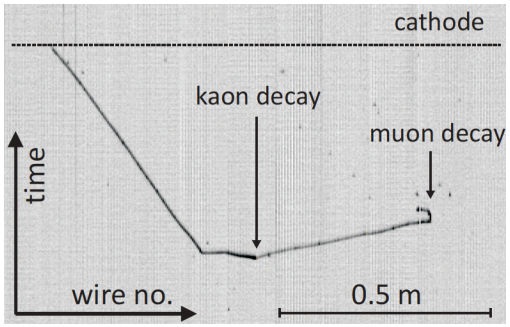
DUNE Far Detector

- The **FD detector design is optimized** (in the energy range of few MeV to few GeV) **for**:
  - pattern recognition
  - energy measurement
  - particle ID
- **Expected measurements**:
  - neutrino mass hierarchy, CP violation and precision oscillation physics with neutrino and antineutrino beams
  - supernova neutrino bursts (unique sensitivity to ν_es)
  - nucleon decay (particularly sensitive to kaon decay modes)
  - atmospheric neutrino oscillations







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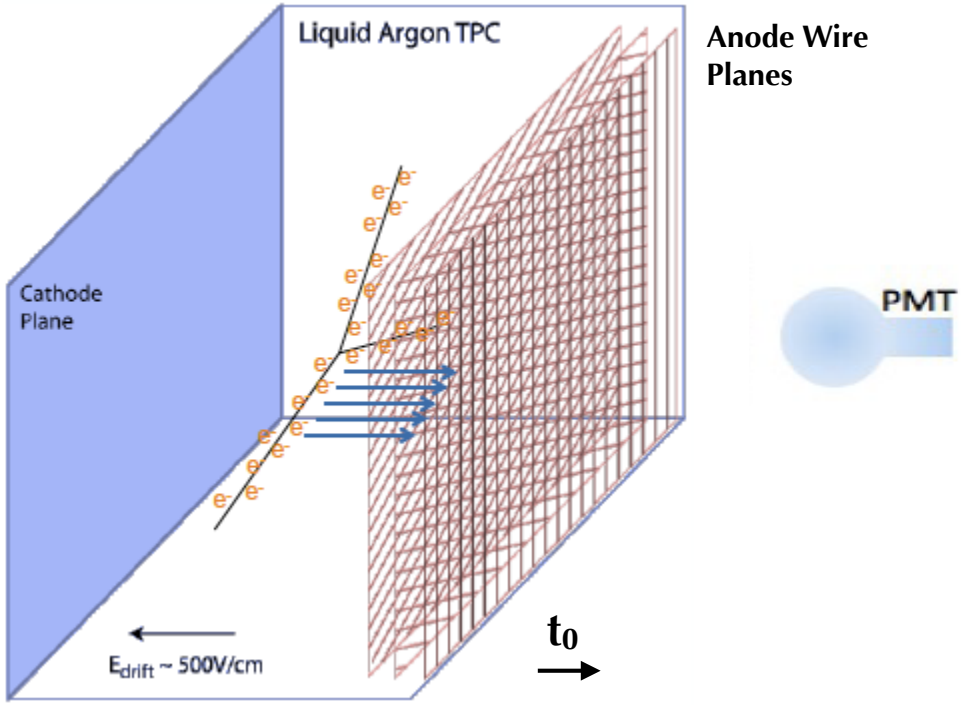
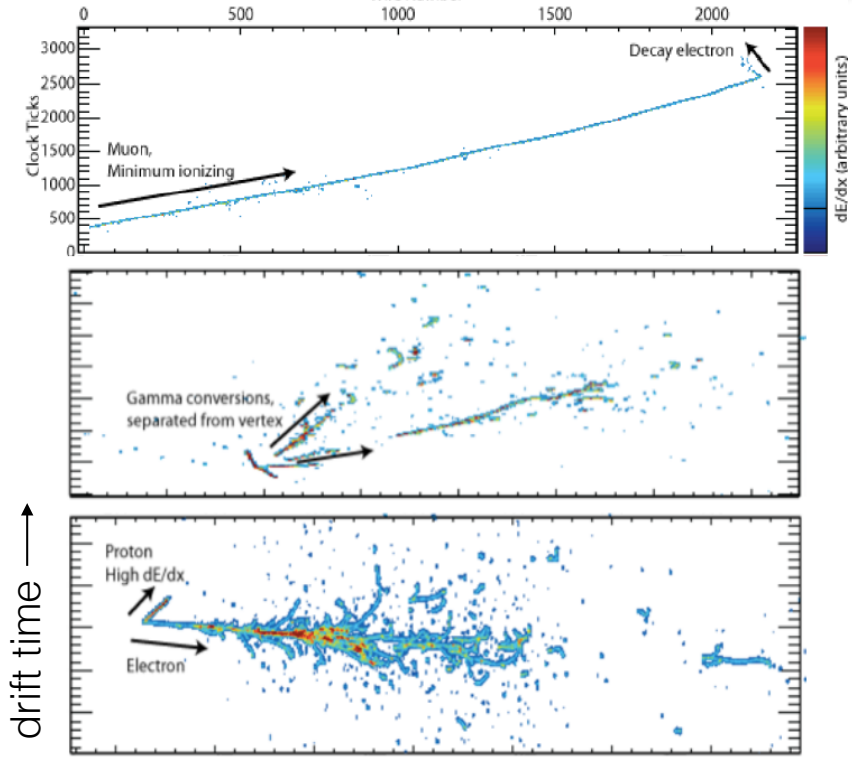
Single-phase LAr TPC detection principle

- Neutrino interactions in Ar produce charged particles that cause ionization and excitation of Argon
  - High electric field drifts electrons towards finely segmented anode wire planes
  - Excitation of Ar produces prompt scintillation light giving t_0 of the interaction
- Technology pioneered and **demonstrated by the ICARUS experiment** (the largest LAr TPC ever operated - 600 ton)

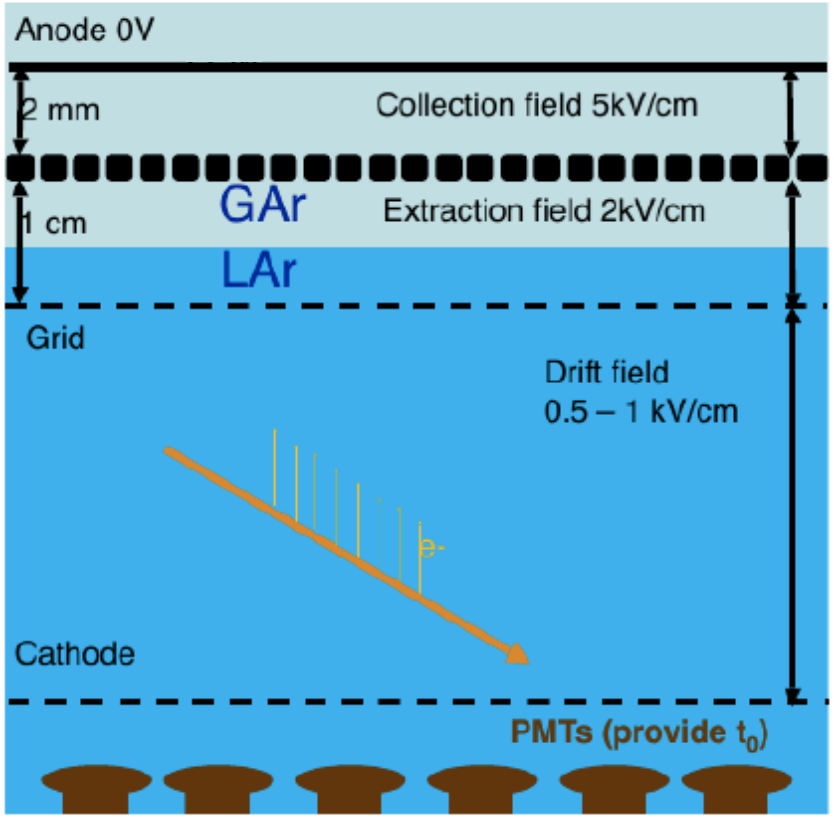


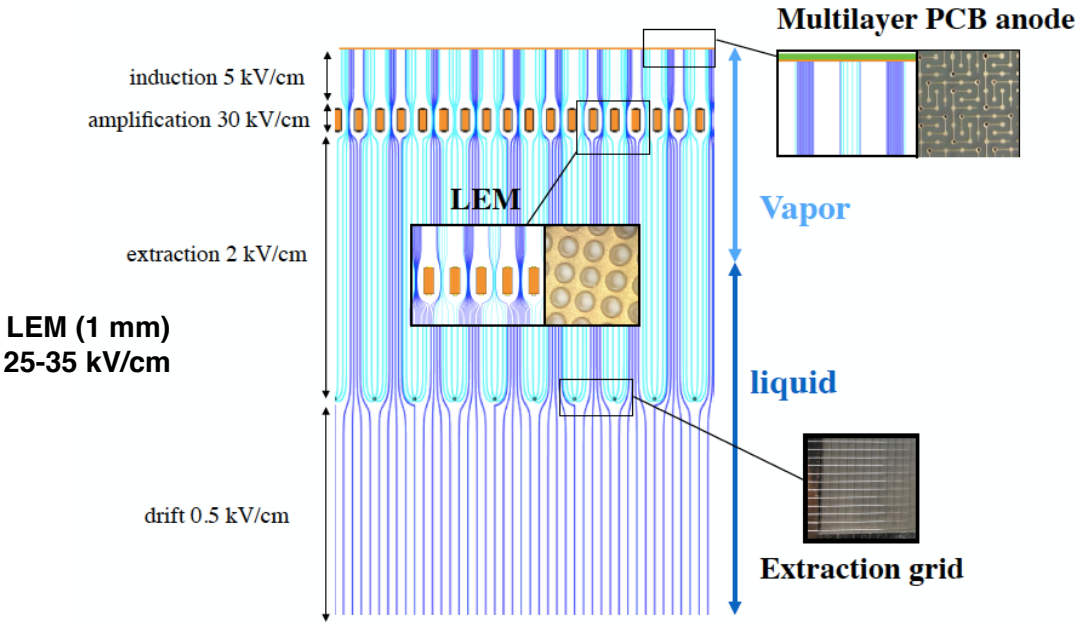
- Independent views provided by multiple wire orientations (2D position information)
- PMTs detect the light produced providing timing information
- 3D reconstruction of tracks and showers
- Time Projection Chamber



Dual-phase LAr TPC principle

Concept of double-phase LAr TPC (Not to scale)





Ionization signals amplified and detected in gaseous argon above the liquid surface

- Ionizing particle in LAr (2.12 MeV/cm for mip)
- Two measurements:
  - **Charge from ionization**: tracking and calorimetry

    Double-phase: multiplication in gas to increase gain and allow for long drift distances (> 5m) and low energy thresholds
  - **Scintillation light**: primary scintillation (trigger and t_0) & secondary scintillation in gas
- Large surface instrumented with PMTs in LAr
- WArP, ArDM, DarkSide, …

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Two proposed technologies

Single-phase
reference design for the CDR

Table 1: Parameters of the DUNE Far Detector LArTPC.

Parameter	Value
Module height	12.0 m
Module width	14.5 m
Module length	58.0 m
channels per APA	2,560
APAs per module	150
Active height (APA)	6.0 m
Active width (APA)	2.3 m
Drift distance in Liquid Argon	3.6m
Drift velocity	1.6 mm/μs
Drift time	2.25 ms
# drifts/readout factor	2.4
readout time	5.4 ms
bytes/sample	1.5
sample rate	2.0 MHz
samples/readout	10,800
# of detector modules	4
Total # of channels	1,536,000

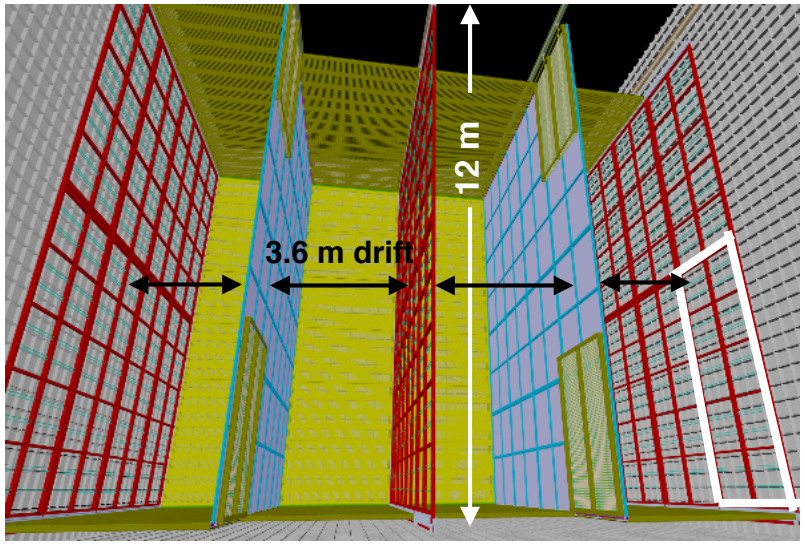
Dual-phase
alternative design for the CDR

Parameter	Value
Full length	60.0 m
Detectors	4.0
channel/CRP	1,920
CRP/detector	80
Active height	12.0 m
Active width	12.0 m
Drift distance	12.0 m
Drift velocity	1.6 mm/μs
Drift time	7.5 ms
bytes/sample	1.5
sample rate	2.5 MHz
# drifts/readout	1.0
Readout time	7.5 ms
Samples/readout	18,750
Total # of channels	614,400

2: Basic parameters of the alternative Far Detector design.

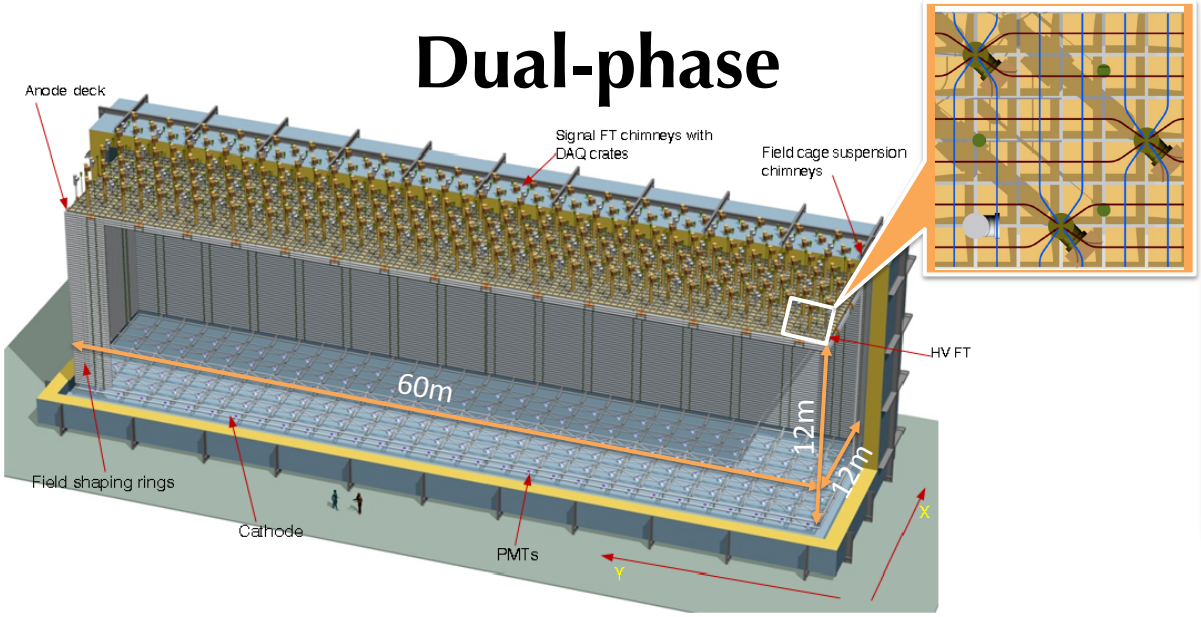
Two detector designs

Single-phase



- 150 Anode Plane Assemblies (APAs)
  - 6 m high x 2.3 m wide
  - embedded photon detection system
  - wrapped wires read out both sides
  - 1 collection & 2 induction wire planes (wire pitch 5 mm)
- 200 Cathode Plane Assemblies (CPAs)
  - 3 m high x 2.3 m wide
- Cathode at -180 kV for 3.6 m drift
- Cold electronics (384,000 channels)

Dual-phase



- 80 3 x 3 m^2 CRP modules at the gas-liquid interface (2D charge collection)
- Hanging field cage and cathode at 600 kV (12 m drift)
- Decoupled PD system (PMTs)
- Finer readout pitch (3 mm), high S/N ratio, lower energy threshold, better pattern recognition, fewer readout channels (153,600), absence of dead material

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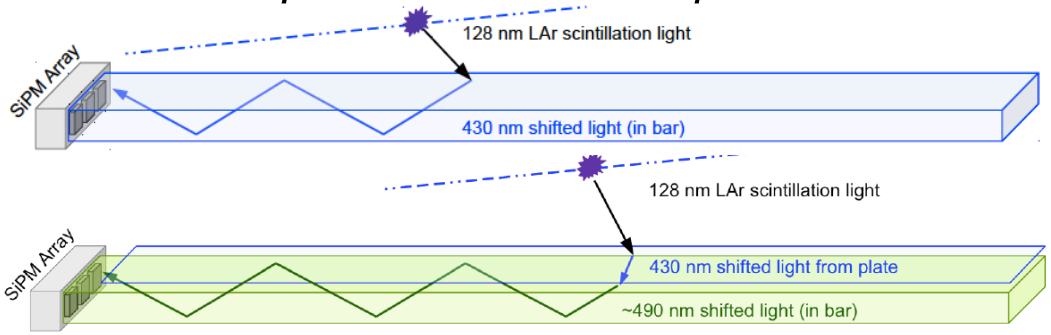
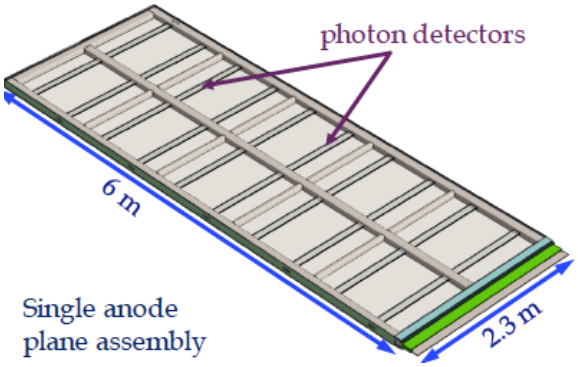
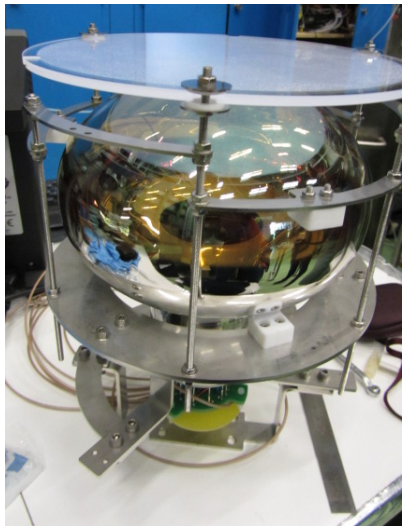
DUNE Photon Detection Systems

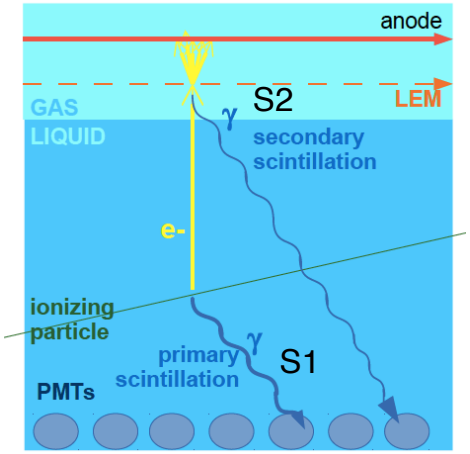
- FD **single-phase** optical detectors: WLS bars + SiPM
  - *Technique under development*

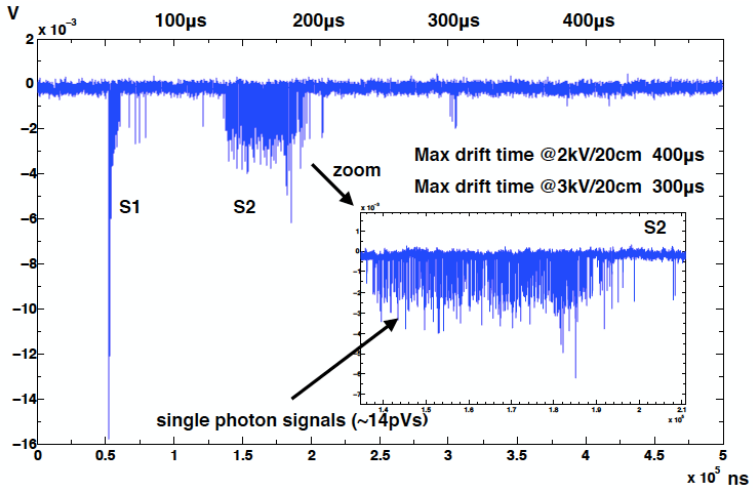




- FD **dual-phase** optical detectors: PMTs with TPB
  - *System well understood*







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ProtoDUNEs at CERN

European Strategy for Particle Physics (2013)

"CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments"

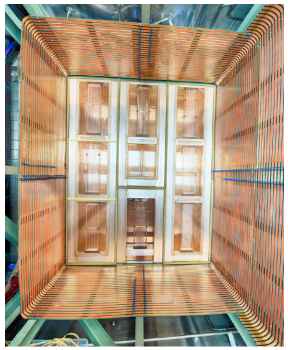
CENF: CERN Neutrino Platform

- A **unique R&D tests facility** of detectors, beams and components
- A new test area is almost finished (EHN1 extension) with charged beams capabilities available in 2017
- **Projects** approved by SPSC:
  - NP01: WA104, ICARUS as far detector for SBN
  - NP02: WA105, demonstrator + engineering prototype for a double phase TPC
  - NP03: PLAFOND, an generic R&D framework
  - NP04: ProtoDUNE, engineering prototype for a single phase TPC
  - NP05: Baby Mind, a muon spectrometer for the WAGASCI experiment at T2K
  - ArgonCube: a modular TPC R&D
- Large **prototyping activities @CENF** on:
  - Large cryostats of a new generation (LNG carrier technology) ~1000 tons LAr
  - Very pure cryogenics at the ppt level, large plants
  - New technologies for LAr Time Proportion Chamber technology (single phase, double phase)
  - Large data sets (similar to LHC-heavy Ions)
  - New photon detector technologies (large area SiPM arrays), interesting for other applications (space, dark matter, telescopes,…)
  - Large size detector engineering integration
  - Automatic pattern recognition (new in the community!)
  - Team/Collaboration building in the Neutrino Community

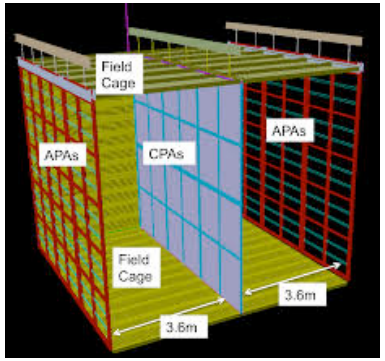
Neutrino Platform at CERN

The DUNE strategy

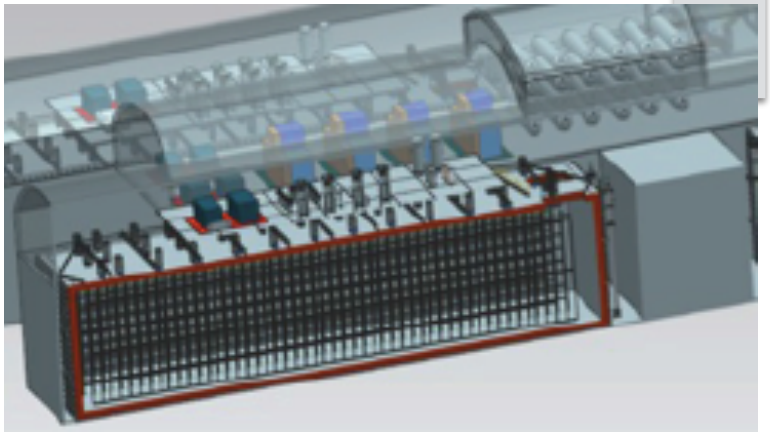
Single-phase



DUNE **35-t** @Fermilab (2015)

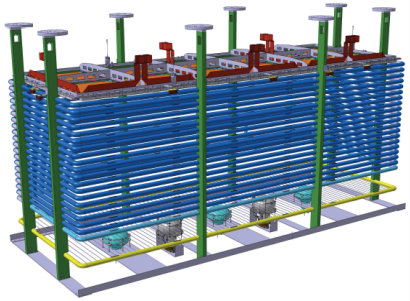


protoDUNE SP
@CERN: 300 ton
(2016-2019)

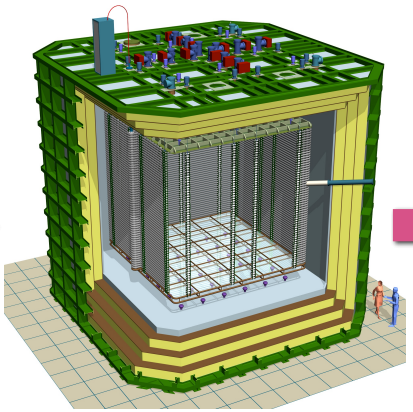


DUNE SP @SURF: 10 kton

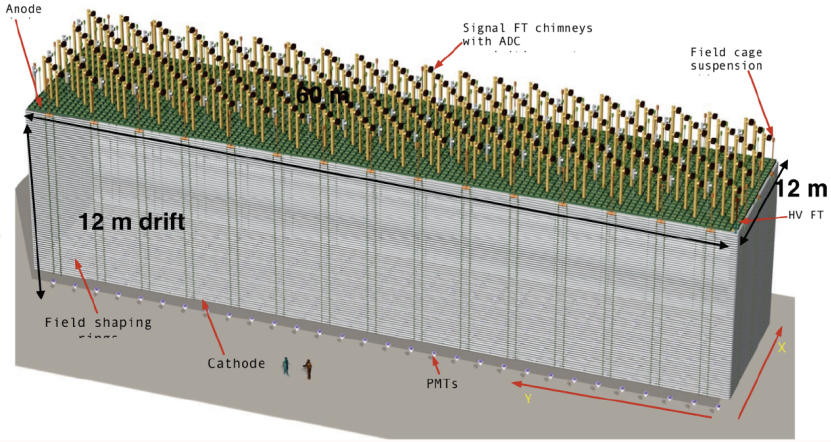
Dual-phase



WA105 **3x1x1 m^3** @CERN:
4.2 ton (2016)



protoDUNE DP
@CERN: 300 ton
(2016-2019)



DUNE DP @SURF: 10 kton

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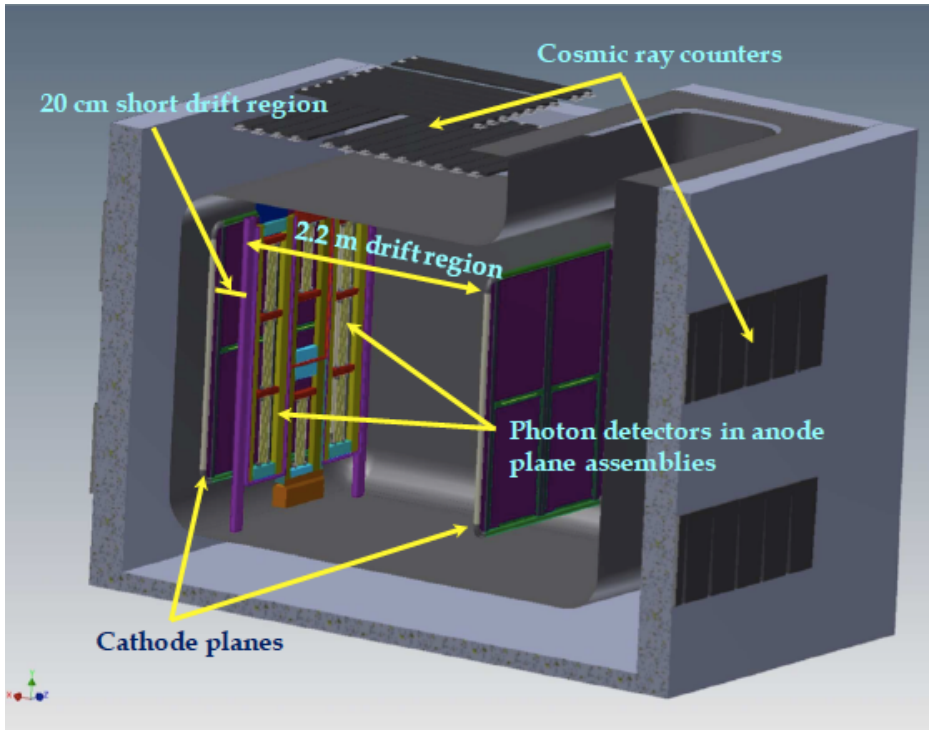
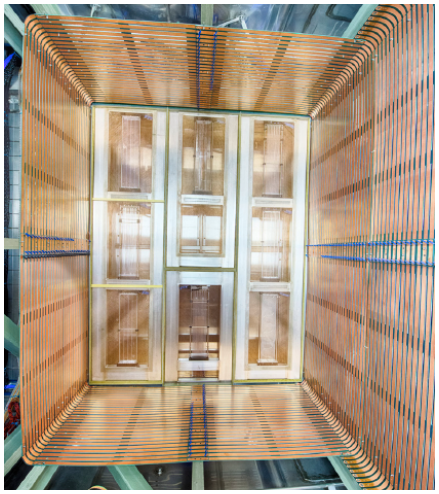
35-ton prototype @FNAL



- First complete system test of DUNE single-phase TPC
- Characteristics
  - 2.5 m x 1.5 m x 2 m active volume
  - 2 drift volumes (long/short)
  - 8 sets of wire planes

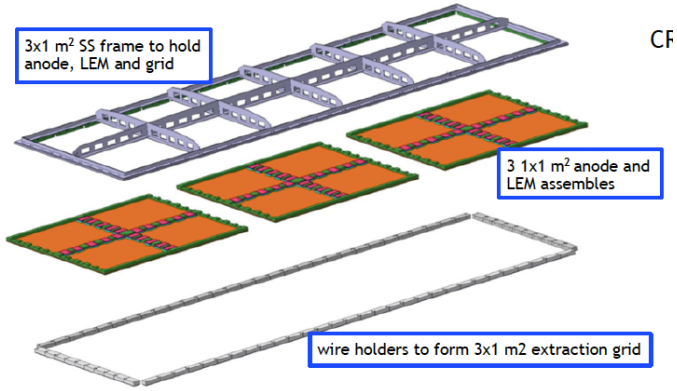


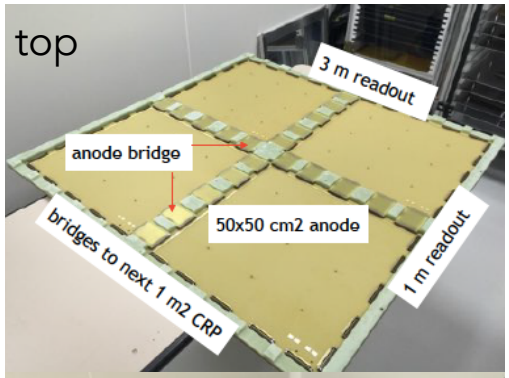
- It includes
  - FR4 printed circuit board field cage
  - Wrapped wire planes
  - Cold electronics
  - Light-guide + SiPM photon detectors
  - Triggerless DAQ (continuous readout)
- Status
  - Filled with LAr (Feb 2nd, 2016)
  - **Operated Feb-Mar 2016 (2nd phase)**
- Results
  - Achieved required LAr purity without initial evacuation
  - TPC/photon detection operated successfully
  - High noise

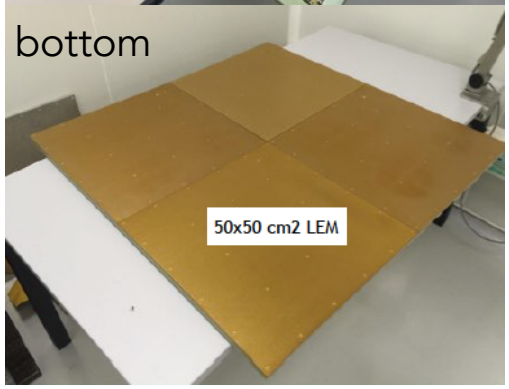
3x1x1 m^3 dual-phase LAr proto

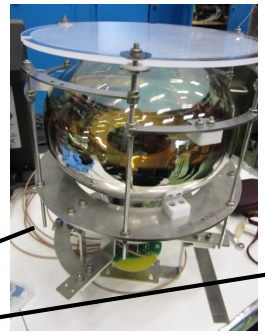
- First large-scale dual phase detector (24 ton LAr in total)
- Assembled in bldg. 182 at CERN
- Installation finished, gas flushing Dec. 2015, LAr filling in Jan. 2017
- Cosmic-ray data taking January-February 2017

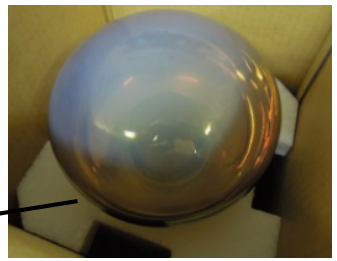
Charge Readout System











- **Light detection system** (5 8″ PMTs)
- Options to be tested: TPB on acrylic plates and TPB on the PMT + positive and negative HV bases

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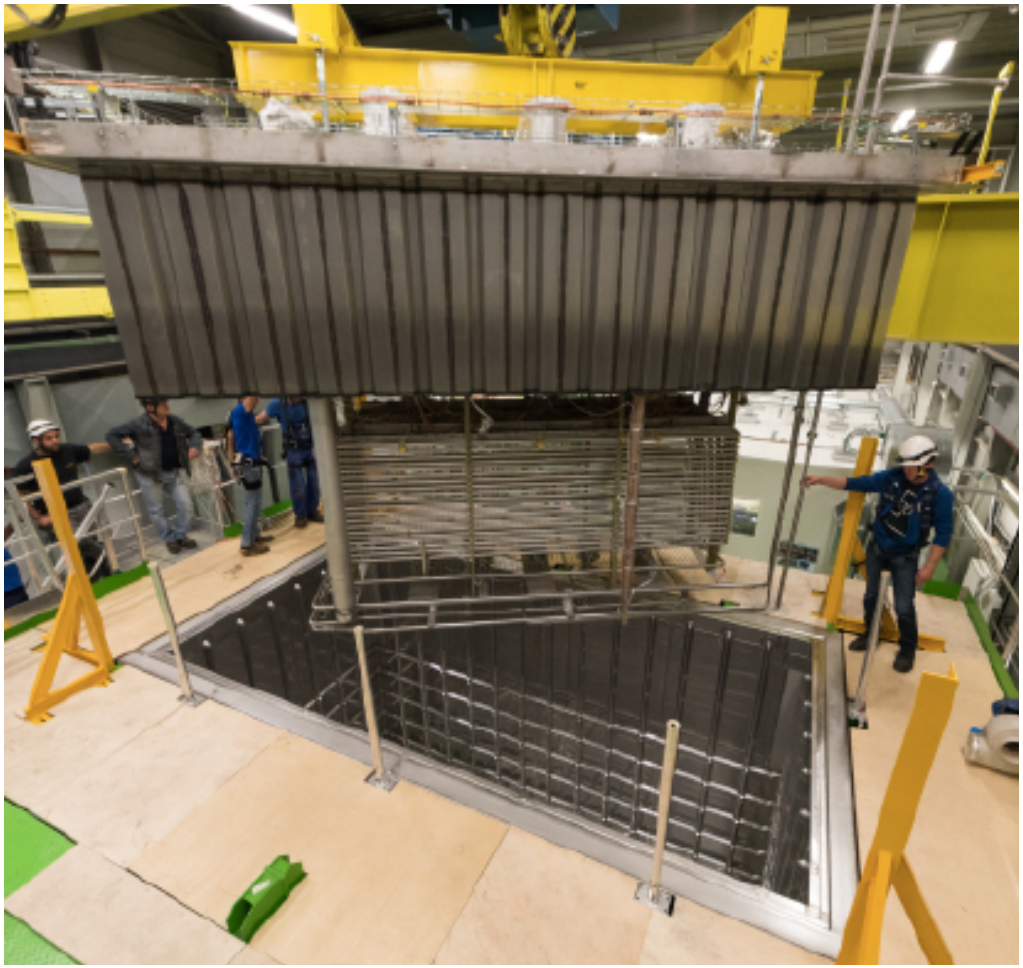
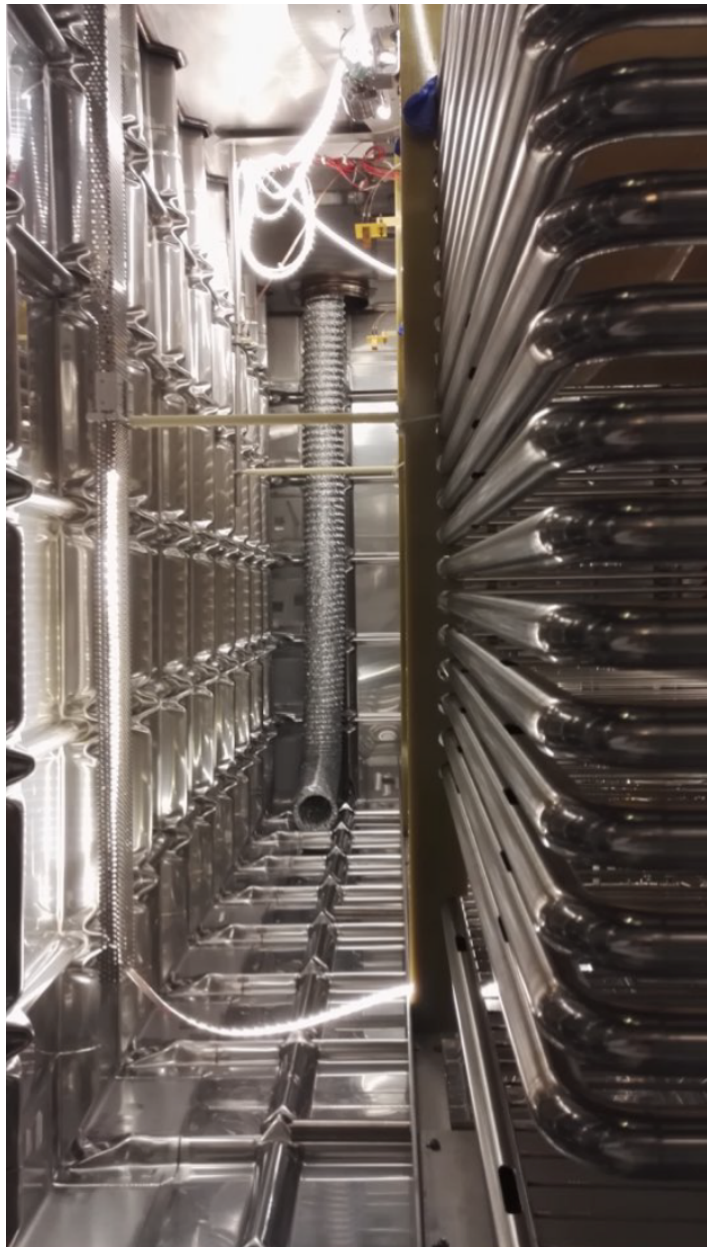
3x1x1 m^3 inside the cryostat

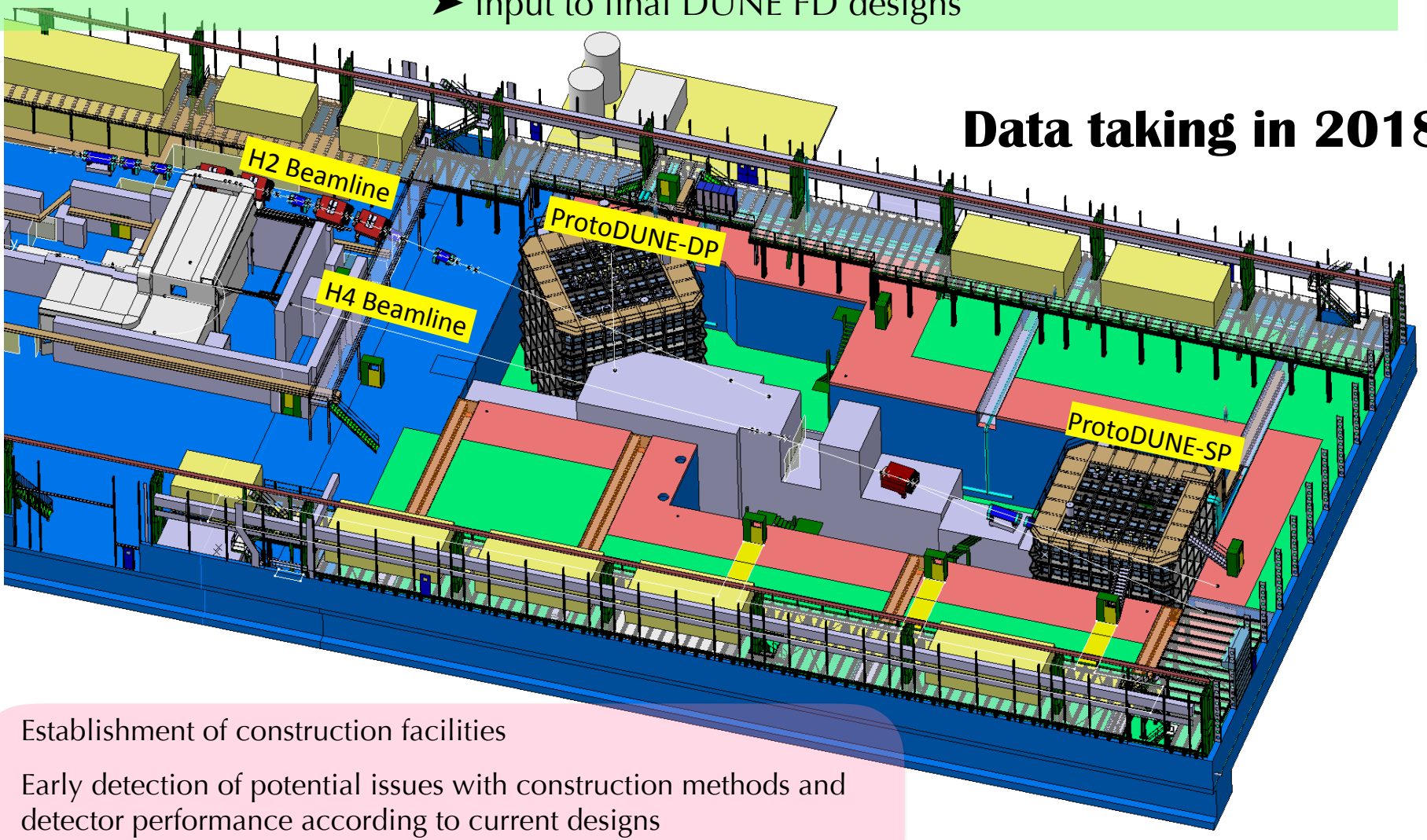




- First prototype of the cryostat membrane based on LNG technology

ProtoDUNEs @CERN

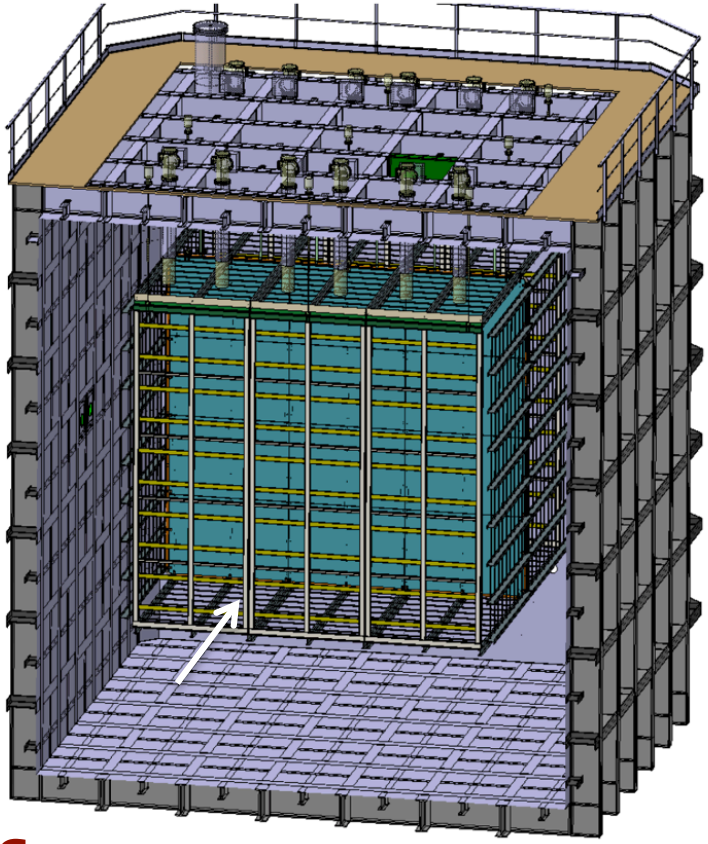
Construction, installation and operation of **single**- and **dual-phase** large scale prototypes
➤ input to final DUNE FD designs

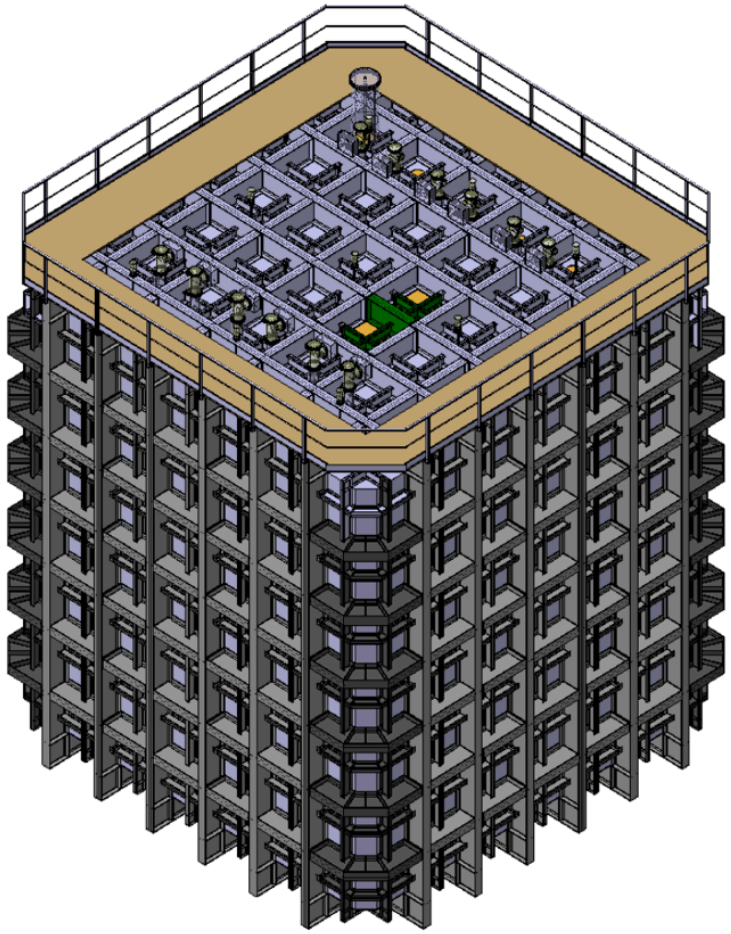


Data taking in 2018

- Establishment of construction facilities
- Early detection of potential issues with construction methods and detector performance according to current designs
- Calibration of detector response to particle interactions in test beam

Single Phase protoDUNE



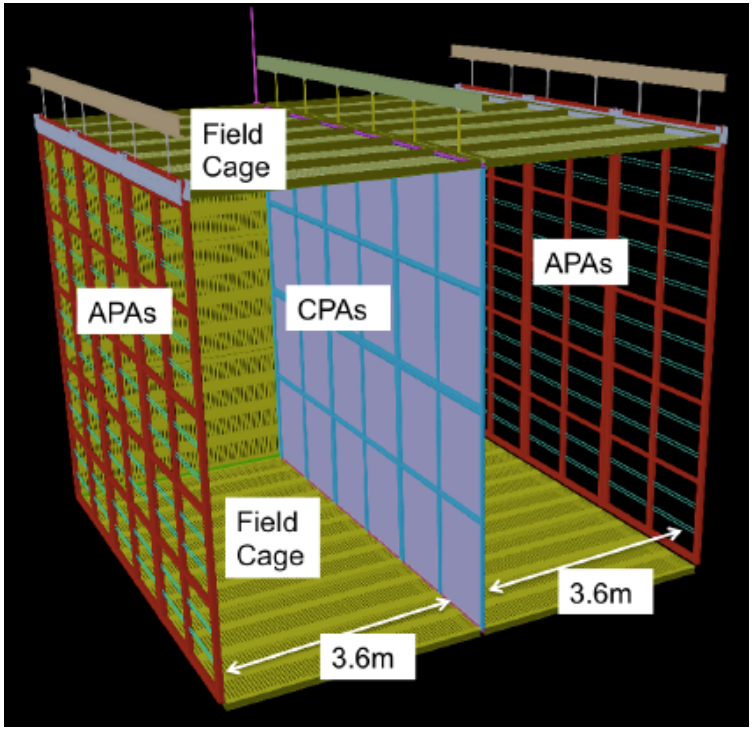


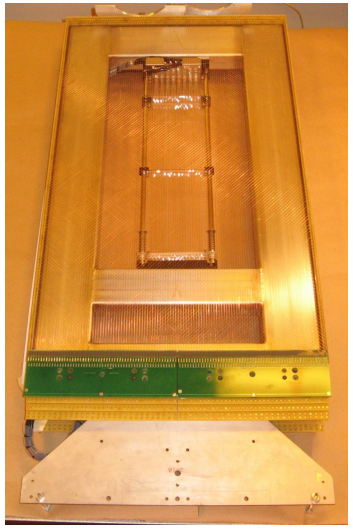
GOALS

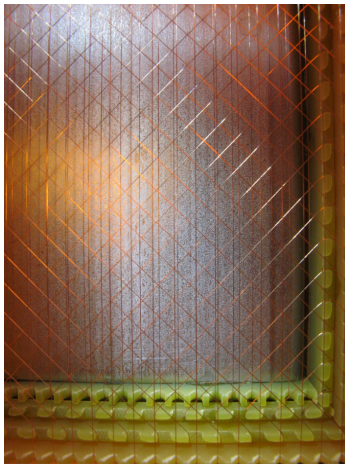
- Demonstrate engineering design, establish construction facilities and installation plans
- Evaluate cold electronics and DAQ strategies
- Characterize detector performance with full-scale components
- Test beam in 2018 with charged particles: particle ID, reconstruction, e/γ separation…

ProtoDUNE SP

- Engineering prototype of DUNE SP TPC using full-scale detector components
- Active volume: 6 m x 7 m x 7 m
- 6 Anode Plane Assemblies (6 m high x 2.3 m wide)
  - Photon detectors integrated into the APAs
  - 10 PD paddles per APA
- 6 Cathode Plane Assemblies (3 m high x 2.3 m wide)
- Cathode at -180 kV for 3.6 m drift (same drift length as in FD)
- Drift field: 500 V/cm
- 15360 total readout wires in TPC
- Wire spacing: 4.79 mm X plane, 4.67 mm U plane, 4.67 mm V plane, 4.5 mm
- Test-beam with charged particles at CERN

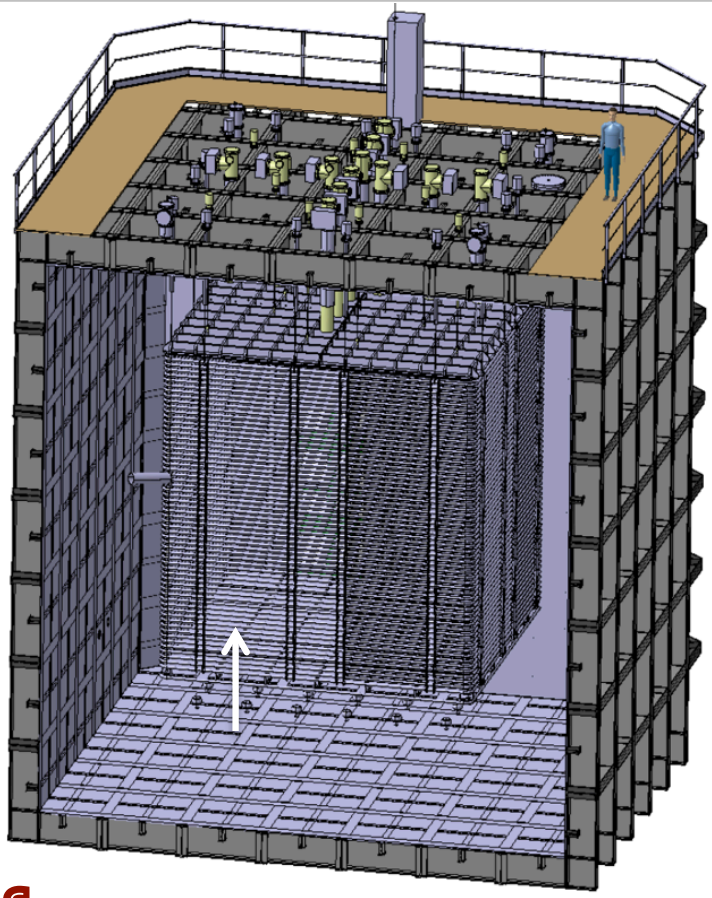


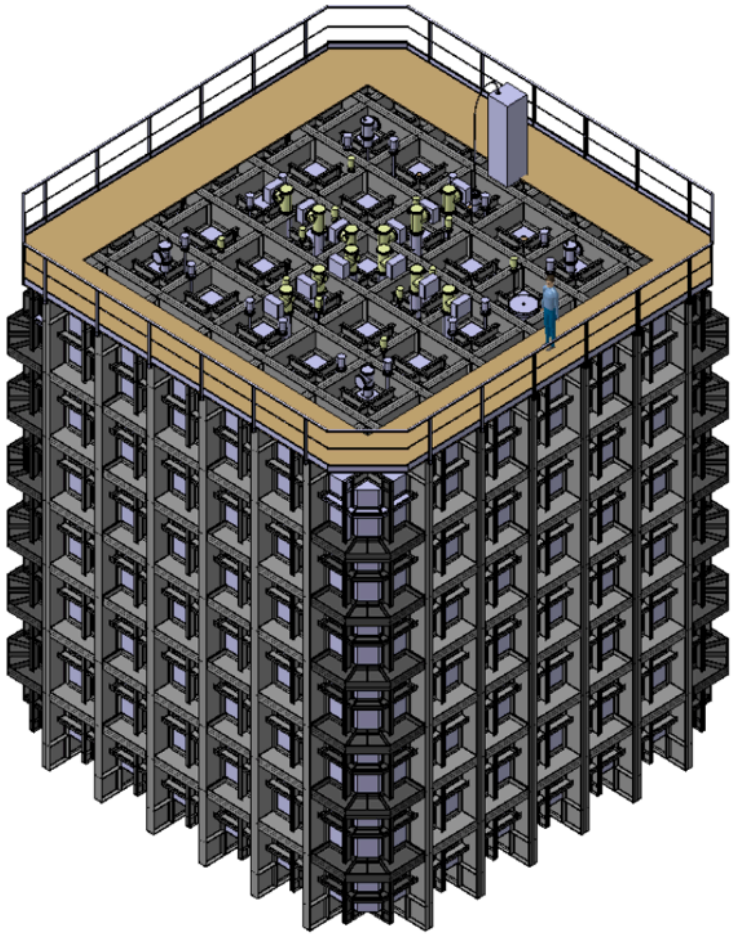




Dual Phase protoDUNE

arXiv:1409.4405



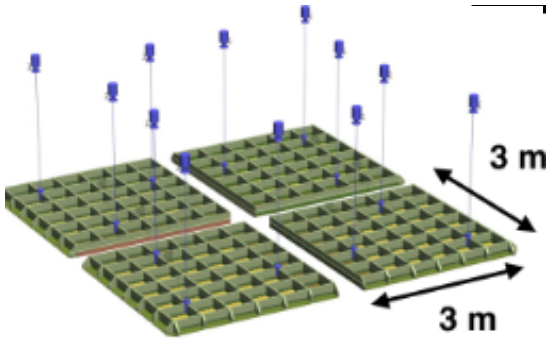


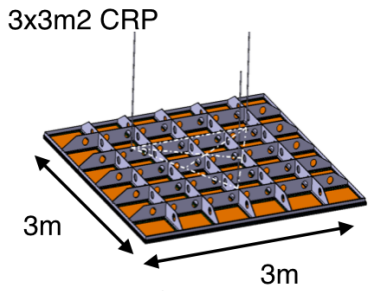
GOALS

- Demonstrate the operation of double-phase LAr detectors at the 100-ton scale
- Test and extrapolate to large scale in an “affordable” way technical solutions:
  - charge readout, long distance drift + HV up to MV scale, purity, UV scintillation light readout
- Test beam in 2018 with charged particles: particle ID, reconstruction, e/γ separation…

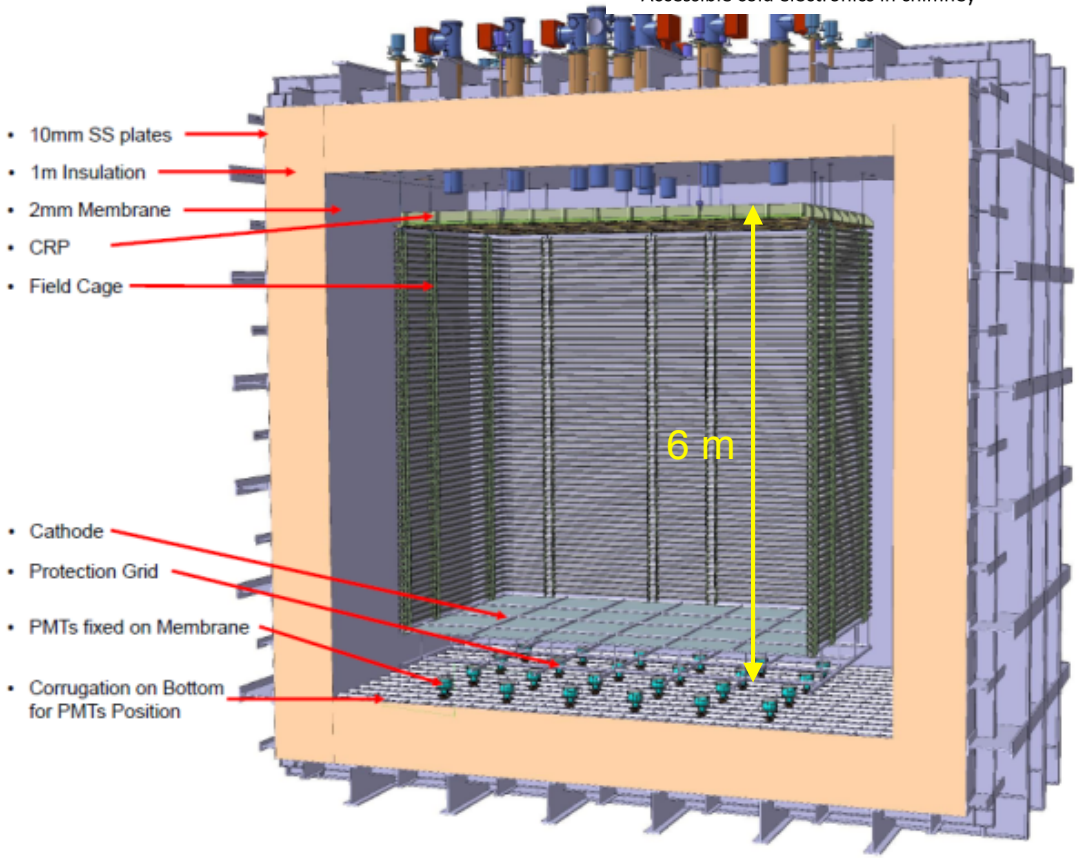
ProtoDUNE DP

- Engineering prototype of DUNE DP TPC
  - 1/20 number of channels of 10 kton DUNE (1/40 volume & data size)
- Active volume: 6 x 6 x 6 m^3
- 6 m x 6 m anode plane made of four 3m x 3m independent readout units
- 6 m vertical drift -> -300 kV cathode voltage
- Drift field: 500 V/cm (extraction field: 2 kV/cm)
- 7680 readout channels
- Validation of construction techniques and operational performance of full-scale DP TPC prototype modules
- Exposure to charged hadrons, muons and electrons beams at CERN (0.5-20 GeV)



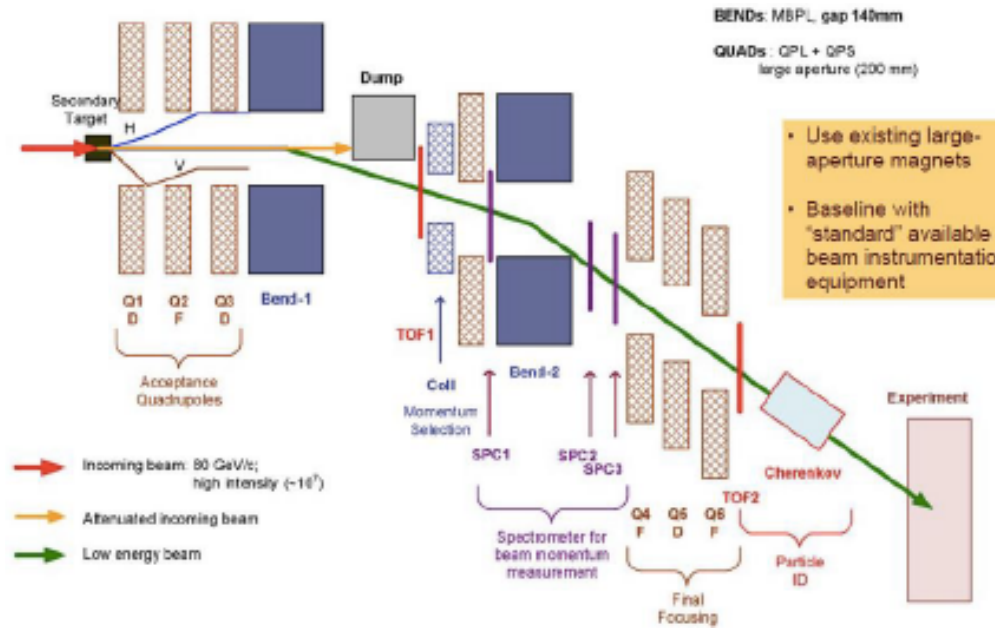


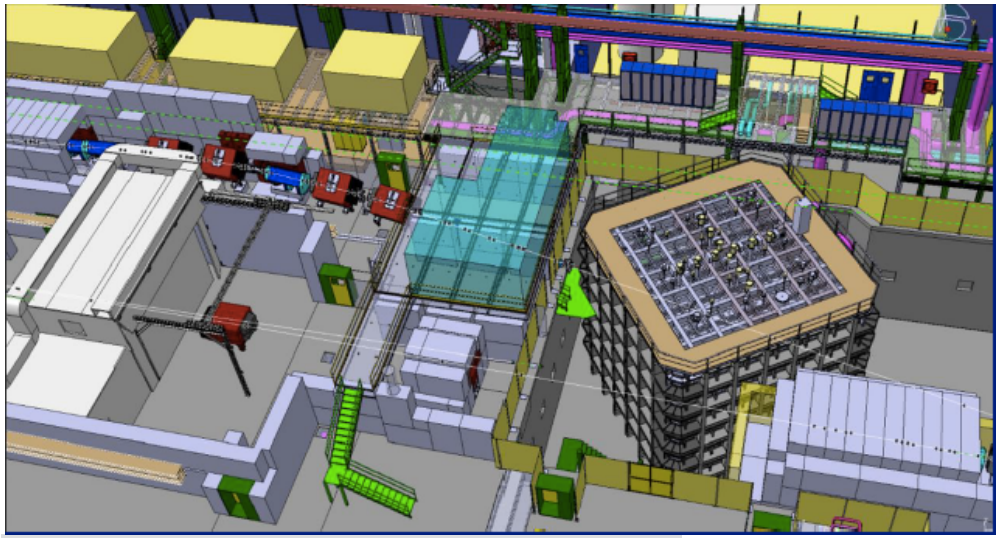
1920 channels/CRP
Accessible cold electronics in chimney



Ciemat

Test beam at CERN





- 2 beam lines in preparation
- Commissioning in late 2017
- Needed to test and optimized the readout methods and calorimetric performance
- Goals:
  - Electron, pion and muon reconstruction
  - Electron/π^0 separation
  - Calorimetry in the GeV range
  - Hadronic secondary interactions to cross check MC models
- The results will help to optimize the final parameters of the DUNE far detector

Conclusions

- Large cryogenic LAr TPC is the technology for future LBL neutrino experiments
- After many years of R&D on smaller prototypes, we are reaching the 1 kton scale
- Small detectors (~100 ton) are being tested in the Booster Neutrino Beam at Fermilab
- Large scale prototypes are being constructed at CERN to be tested with charged particles beam in 2018
  - Single and dual-phase LAr technologies will be compared
- Scalability is possible since prototypes are constructed following a modular approach
- DUNE will represent the realization of very large LAr TPC detectors (40 kton active) for the next generation LBL neutrino experiments